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Governor

ADVANCED GAS APPLIANCE DEVELOPMENT

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions. PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Advanced Gas Appliance Development/Final Report is the final report for the Advanced Gas Appliance Development project (contract number 500-05-011), conducted by The Gas Technology Institute. The information from this project contributes to PIER's Buildings End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

The purpose of this project was to develop new products and technologies to support energy efficiency gains in the commercial food service marketplace. The scope covered five products: tankless water heaters, commercial gas fryers for foodservice, commercial underfired charbroilers, commercial over-fired broilers, and hybrid optimized tankless water heating systems.

The methods used in this project included literature surveys and interviews, technology assessments, prototype development, laboratory and field testing, and feedback from cooking professionals.

The major findings for tankless water heating show good marketplace experience, but also identified areas for improvement. For the gas fryer, cooking energy efficiency of 60 percent was achieved in testing, supporting commercial use of the technology. For the underfired charbroiler, 50 percent energy savings was achieved, but the performance is highly dependent on cooking variables. For the over-fired broiler, a 25 percent reduction in energy consumption was projected based on a preliminary design and recommendations for further development. For the hybrid optimized tankless water heater, an energy factor of 0.71 to 0.73 was supported.

The results of the investigation were used to identify new product opportunities, development needs, and areas for technology advancement. Some of the development activities involved manufacturing partners who are commercializing the appliances.

Keywords: commercial food service, water heating, tankless water heating, gas fryer, underfired charbroiler, over-fired broiler, hybrid optimized tankless water heater

1.0 Executive Summary

Introduction

Commercial foodservice employs 1.5 million people in California in more than 100,000 establishments, according to the National Restaurant Association. This large industry uses five times more energy per square foot than typical commercial spaces, offering a significant energy savings opportunity. The technology baseline for commercial foodservice appliances is very low, with full load efficiencies in the 20 to 30 percent range and in-kitchen utilization efficiencies in the 5 to 10 percent range. High cooking temperatures and always-on control systems are the rule. Of the 800,000 commercial cooking appliances installed and operating in California, roughly 70 percent are powered by natural gas with few ENERGY STAR® equipment options. Most water heaters installed in food service facilities just meet the minimum efficiency standard. The potential to reduce energy use for water heating in commercial operations is significant – estimated at 50 million to 100 million therms per year with effective Public Interest Energy Research (PIER) and market transformation. The opportunity for efficiency improvement through technology development for this sector is very significant, offering good payback for the research and development investment.

This report summarizes the results of five tasks conducted by the Gas Technology Institute for the California Energy Commission, PIER Building End-Use Energy Efficiency Program project CEC-500-05-011. All of the tasks targeted advanced gas appliance development. Summaries of the five projects are contained in this report and detailed task reports are published on the Energy Commission website. The task reports are referenced in each project report section and the citations are included in the list of references.

Purpose

The purpose of this project was to investigate technology opportunities in five key product areas impacting the commercial food service marketplace:

1. Tankless water heaters
2. Commercial gas fryers for foodservice
3. Commercial underfired charbroilers
4. Commercial over-fired broilers
5. Hybrid optimized tankless water heating systems

The results of the investigation were used to identify new product opportunities, collect data from the laboratory or the field, and pursue design options into a design or prototype phase. For several of the product areas, the team made an assessment of the opportunity for new products or pursued new product development opportunities with commercial partners.

Project Objectives

Each project had specific objectives focused on the need to advance new technology to reduce energy use in the commercial food service marketplace.

The objective of the tankless water heater project in task 2 was to establish a baseline for public knowledge about tankless water heaters that can be used to identify further research or product development opportunities. This objective was achieved by providing an annotated review of available information on current tankless water heaters available at the time of the research, filling in informational gaps, and then exploring technical and market issues and opportunities for tankless water heater technology in California.

The objective of the commercial gas fryer for foodservice project in task 3 was to develop a gas fryer that reduces energy costs, improves performance, and reduces oil consumption. Through reduced-oil cooking, also providing benefits for reducing trans-fats, a low oil volume fryer with advanced heat exchange was designed with a cooking energy efficiency target of 60 percent, which would qualify for ENERGY STAR label.

The objective of the commercial underfired charbroiler project in task 4 was to increase the real-world cooking efficiency of gas charbroilers above 5 percent and reduce the heat gain to the space proportionally, without impact to the cooking characteristics of the device or changing the look or flavor of the cooked products. This objective was to be addressed by designing an advanced charbroiler with retractable hood and thermostat control to improve performance while maintaining the unique cooking characteristics of the device.

The objective of the commercial over-fired broiler project in task 5 was to improve the design of the gas-fired over-fired broiler to reduce energy consumption by 25 percent and reduce heat gain to the air conditioning system. This objective was to be met without impacting the quality, the cooking process, or the look of the wide variety of products that are cooked with gas over-fired broilers in commercial kitchens.

The objective of the hybrid optimized water heater project in task 6 was to develop prototype specifications for a high efficiency hybrid water heater based on existing tankless and conventional storage units coupled with innovative design and control strategies. Additional objectives were to provide stable water temperature on demand for dynamic loads and flow rates, peak and total water draws, and variable inlet water temperatures.

Project Outcomes

Each project also had specific outcomes addressing its project objectives. A common thread among outcomes was development of data or design information that enables advancement of the technology and reduction in energy consumption.

The outcomes of the tankless water heater project in task 2 were a literature review establishing a baseline for information available on tankless water heaters summarized in nine key findings, and a summary of 20stakeholder interviews identifying needs and opportunities. The literature review and interviews supported the durability of the product based on good marketplace experience, but they also identified opportunities for improvement.

The outcomes of the commercial gas fryer for foodservice project in task 3 include assessments from the earliest stages of product development through creation of marketing materials. The outcomes were: the identification of key design factors, a preliminary concept, a prototype fryer design and test results, a fryer functional specification, a computational fluid dynamics model, a second prototype design and test results, and marketing materials. All outcomes supported the viability of the concept proposed here for cooking performance and 60 percent cooking energy efficiency.

The outcomes of the commercial underfired charbroiler for foodservice project in task 4 start with the early stages of product development and conclude with feedback from field testing. The outcomes were: the identification of "must have" design and performance factors, a built prototype, laboratory performance data, and chef feedback from testing in two commercial kitchens. The results supported the 50 percent energy savings opportunity of this technology with minimal impact to product quality and cooking practices.

The outcomes of the commercial over-fired broiler project in task 5 included preliminary design specifications for the new burner and catalyst system concepts, drawings for the burner concept, and recommendations for further development to achieve the 25 percent reduction in energy consumption target.

The outcomes of the hybrid optimized water heater project in task 6 were: the list of prototypes for fabrication, the testing plan for evaluations of those integrated systems in the laboratory, new modeling capabilities to narrow the range of hybrid design parameters, completion of the hybrid water heater breadboard testing apparatus, detailed and finalized test plan, and documentation of testing results. The outcomes support the projected Energy Factor (EF) of 0.71 – 0.73, supporting a more economically viable efficiency upgrade than tankless water heaters in retrofit applications.

Conclusions

The five projects included in this report share conclusions supporting the use of advanced technology in water heating and commercial food service equipment to focus energy on the water heating or cooking load while minimizing off-cycle losses. The equipment efficiency upgrades were supported without sacrificing other performance metrics. In the case of the tankless and hybrid optimized water heater, directly heating water for consumption while providing a minimum storage volume provides an improvement in efficiency, avoids cold draws, and reduces jacket losses. In the fryer project, design improvements reduce oil volume requirements from 50 pounds to 35 pounds, achieve ENERGY STAR cooking energy efficiency of 60 percent, and offer improved cleanability. In the underfired charbroiler project, the cooking efficiency achieved with new burners, hood, and thermostat was approximately 50 percent better than the conventional charbroiler, ranging from 39 percent to 52 percent cooking efficiency. In the over-fired broiler project, the redesign using the flat radiant panel burner, recuperation, modulation, and secondary radiant surface show promise in achieving the targeted 25 percent energy reduction from a typical broiler. Further prototyping and testing is needed to confirm the energy savings potential.

Recommendations

Recommendations from the two water heater projects support the next steps in product development and testing now being conducted in a related Energy Commission project at the Gas Technology Institute. The tankless and hybrid optimized tankless water heater projected energy savings requires laboratory validation, vent system categorization, and NO_x testing to meet South Coast Air Quality Management District emission limits of 10 ng NO_x /J output (or 14 ng NO_x /J output if over 75,000 Btu/hr firing rate). First cost and installed cost must be quantified to establish the cost effectiveness of this level of EF upgrade, especially in retrofit applications.

Recommendations from the three commercial food service projects also support the next steps in product development and testing recently awarded to the Gas Technology Institute by the Energy Commission. The fryer project has achieved its energy savings targets in the prototype stage in laboratory testing and would benefit from commercial-grade product design and testing in a food production environment. The underfired charbroiler project team recommendation is to pursue an advanced design with Royal Range and conduct field testing with the support of California utilities to quantify the energy savings and cooking benefits of the new design. Recommendations for the over-fired broiler development are to pursue prototyping and production with one of two California Manufacturers: the Montague Company or Royal Range. There are many issues to be resolved regarding the operation of the burner, which include:

- Cold and warm start ignition
- Response of the controls
- Characterization of efficiency and heat flux at various firing rates.

Benefits to California

The benefits to California of successful deployment of a new hybrid optimized tankless water heater products are significant. Water heater manufacturers have cited the need to provide a continuum of cost-effective product offerings over the energy factor range in order to stimulate efficiency upgrades beyond federal mandated minimum levels. In the Energy Commission sponsored Super Efficient Gas Water Heater Appliance Initiative, it was reported that “the replacement rate of close to a million units per year in California alone creates the potential to rapidly improve gas storage water heating efficiency … [and] reduce annual gas consumption by 17– 29 percent”. However, tankless water heaters in the 0.80 energy factor range and above, that can achieve the higher end of this range of savings, have been significantly limited in their market penetration by technical issues and cost. A hybrid product can help California reduce gas consumption over time in the commercial or residential water heating marketplace.

In the three commercial food service products, the benefits to California are related to the significant efficiency improvements in this often-overlooked sector. Benefits to the state of California for the gas fryer are a 15 percent energy savings opportunity for the 200,000 installed units. Using a 10 percent market penetration for the product outlined in this report, annual energy savings would be 3 million therms per year. Benefits to California from the underfired charbroiler project is a savings of 500 therms per year per charbroiler or about 2 million therms per year with 20 percent market penetration. Carbon dioxide emission reduction of 10 million metric tons is also possible. For gas over-fired broilers, approximately 20 percent of the 170,000 total installed devices are in use in California. The redesigned broiler could result in a 25 percent reduction of the 1100 therms/yr that typical broilers use. If 10 percent of the existing units are replaced with the new broiler, approximately 1 million therms per year would be saved in California alone.

2.0 Task 2: Tankless Water Heater

2.1. Introduction

The objective of Task 2, Tankless Water Heaters, was to establish a baseline for public knowledge about tankless water heaters that can be used to identify further research or product development opportunities (Kalensky 2009). This objective was achieved by providing an annotated review of available information on current tankless water heaters available at the time of the research, filling in informational gaps, and then exploring technical and market issues and opportunities for tankless water heater technology in California.

2.2. Subtask 2.1: Literature Review

2.2.1. Introduction

The objective of this task was to establish a baseline of public knowledge by providing an annotated review of available information on current tankless water heaters.

2.2.2. Approach

To accomplish this task objective, the Gas Technology Institute (GTI) used the approach outlined below in its literature review of publicly available information:

1. Collect, review, and report findings from literature related to tankless water heaters available in the public domain including:
    - Domestic and international studies, surveys, evaluations,
    - Manufacturers' appliance product literature, and
    - Codes and standards, policy, regional planning initiatives.
2. Based upon the literature review, characterize the state-of-the-art in tankless water heaters, and identify knowledge gaps and issues for further investigation.

2.2.3. Outcomes

To implement this work plan, GTI organized the collected literature by the types of information sources listed in Table 1.

Table 1. Literature Search Summary

Information Sources	Documents Reviewed
3rd Party Evaluations	12
Manufacturers' Literature	25
Relevant Codes & Standards	19
Water Distribution Studies	10
Water Usage Studies	26
Total	92

Source: Gas Technology Institute

The literature search used key words and themes associated with tankless water heaters, employing a variety of search engines, including major commercial and institutional based search engines. This method produced extensive results on all types of information sources except third party evaluations. Most third party evaluations obtained were through direct contact with the author or funding institution. Additional information was obtained from websites, trade journals, and magazines.

This literature review was conducted for the California Energy Commission to establish a baseline public knowledge about tankless water heaters by providing an annotated review of available information on current tankless water heaters. The key findings of the literature review include:

- The new construction market is most favorable to gas tankless water heaters rather than the replacement market since upfront design considerations can minimize installation cost adders that can include ¾ inch gas piping, specialized venting, greater combustion air requirements, and electric connections. Some costs adders are make and model dependent.
- In 2005, manufacturers estimated tankless market share up to 2 percent of annual shipments or 11 thousand units annually in California, however, appliance saturation studies in 2000 and 2005 suggest that California has a higher percentage of the annual U.S. tankless sales, perhaps 28,000 units per year.
- The most critical aspects to maintaining tankless water heater performance are similar to those of storage water heaters and include water quality, proper sizing, selection of model, qualified installer, quality of installation, and proper maintenance.
- Market growth enhancers for gas tankless water heaters include higher efficiency (than standard storage water heaters), continuous hot water, long projected life, lower energy costs, compact design, rebates and incentive programs.
- Market growth inhibitors for gas tankless water heaters include first cost, installation cost-adders, required periodic maintenance by qualified professionals, and an immature market and service infrastructure.
- The first-cost premium of gas tankless water heaters diminishes when compared to high efficient storage water heaters; however, cost adders may remain.
- The improper use of a tankless water heater voids the warranty. It is important to verify that the intended application is covered by warranty. Some tankless water heater models are approved for residential domestic hot water use only and may not be approved for other applications such as solar/preheat backup, high temperature booster use, hydronic heating, or for use in recirculation systems and commercial applications.
- Gas tankless water heaters could have different emission requirements than residential gas storage water heaters. South Coast Air Quality Management District (SCAQMD) proposed 2012 tankless NO_x emission limits of 20 ppm (14ng/joule of heat output) are not as stringent as 2007 residential storage NO_x emission limits of 10 ng/joule of heat output.

- Un-optimized hot water distribution system designs and sub-par building practices that result in long un-insulated hot water pipe runs can reduce the perceived tankless water heater performance due to increased hot water delivery wait times, water usage and energy waste. Actual tankless water heater performance will be reduced from what is measured in the Department of Energy (DOE) Energy Factor (EF) test if there are many hot water draws per day. Averages of 20-80 hot water draws per day have been recorded in recent hot water usage studies.

2.3. Subtask 2.2: Stakeholder Interviews

2.3.1. Introduction

The objective of this subtask was to confirm literature review findings regarding tankless water heaters through interviewing manufacturers and installers to obtain supplemental information.

2.3.2. Approach

Interviews with manufacturers and plumbers were conducted to confirm literature review findings regarding tankless water heaters, fill in informational gaps, and explore technical and market issues for tankless water heater technology in California. The following approach was used:

- In-Depth Interview Topic Guides were developed to guide discussions with tankless water heater manufacturers and plumbers. The topic guides explored key areas including but not limited to:
  - Domestic hot water usage (appliances, lifestyle, and distribution systems)
  - Technical issues including capacity, burners, power requirements, controls, installation and maintenance, and
  - Market issues including competition and codes and standards
- Six water heater manufacturers that manufacture or sell gas whole-house tankless water heaters were interviewed following the *In-Depth Interview Topic Guide for Manufacturers"*.
- Fourteen plumbers that sell, install, and service gas whole-house tankless water heaters were interviewed following the *In-Depth Interview Topic Guide for Plumbers*.

2.3.3. Outcomes

In-depth interviews with six manufacturers and fourteen plumbers from December 2006 through February 2007confirmed literature review findings regarding gas whole-house tankless water heaters (tankless), filled in informational gaps, and explored technical and market issues for tankless water heater technology in California. Listed below are key findings.

Manufacturers

Manufacturers surveyed predict consumer-based demand for tankless water heaters growing in future years at a rate of about 10 percent to 15 percent, down from 2006 and 2007 (30 percent). Strong markets for tankless water heaters include California (50 percent retrofit, 50 percent new construction), Texas and the Southeast (primarily new construction), and the Northeast (primarily retrofit).

- "Endless Hot Water," consumer demand for lower energy bills, the space saving attributes of tankless water heaters, and efficiency are key market drivers.
- Installation costs, first-cost, water quality, and ensuring quality installations are limiting factors in tankless market growth.
- Near- to mid-term solutions to improve market share include reducing electric power consumption, and enhanced back-up power options for operation during a power outage.
- Mid- to long-term solutions to improve market share include reduced first cost, broader applications, and lower installation costs.
- Manufacturers view hot water distribution design tools, ultra-low NO_x burners, and retrofit cost reduction as priority areas for public research.

Plumbers
Fourteen plumbers were surveyed about the types of hot water distribution systems they work with or install.

- Rigid copper pipe in a traditional trunk and branch configuration is the predominant hot water distribution system.
- While 85 percent of the plumbers insulate the hot water pipes using ¾" black closed-cell foam 80 percent of the time, a large portion of the pipes in the conditioned space (50 percent) and under the slab (43 percent) do not get insulated.
- 25 percent of recirculation systems installed are continuous operation.
- Plumbers surveyed report that customers want hot water systems that are reliable and durable, energy efficient with low maintenance, and consistent in delivering hot water at adequate pressure when needed.
- Tankless water heaters provides plumbers an advantage in resolving customer needs for endless hot water, saving space, efficiency, and lower energy bills.
- In comparing tankless water heaters to storage:
    - Tankless water heaters are slightly more difficult to install in both residential and commercial new construction due to pipe size and cost, but tankless may have an advantage complying with the California seismic code.
    - Tankless water heaters are more difficult to install in both residential and commercial retrofit due to added cost, time, and complexity in gas, water, and venting modifications.
    - Tankless water heaters are slightly less reliable in meeting hot water demand in both residential and commercial installations.
    - Tankless water heaters are slightly less stable in delivering hot water in both residential and commercial installations.
- Plumbers surveyed report frequent maintenance issues including heat exchanger flushing or deliming, and inlet-filter cleaning.

- Plumbers surveyed report customer dissatisfaction, both residential and commercial, for the high cost of tankless, and the inability to operate in a power outage. Residential customers also cited the time delay between breakdown and repair.
- Customer cited lifestyle changes due to tankless use including the inability to take a shower during a power outage, a longer wait time for hot water, a limit on simultaneous hot water use, and running multiple fixtures to induce hot water flow.
- Plumbers consider water quality and the wait time for hot water flow as factors that could limit future residential market growth if not addressed.
- Plumbers consider the uncertainty in expected service life, poor performance, insufficient hot water flow, and the retrofit market as factors that could limit commercial tankless market growth if not addressed.
- Plumbers surveyed report that both residential and commercial customers are generally satisfied with gas whole-house tankless water heaters. All plumbers surveyed would recommend tankless to customers.

2.4. Tankless Water Heater Conclusions and Recommendations

The conclusions of this task are as follows:

- The new construction market is most favorable to gas tankless water heaters since upfront design considerations can minimize installation cost adders such as increased gas pipe size, specialized venting, combustion air requirements, and electric connections.
- The replacement market offers challenges to gas tankless water heaters since most replacements are like-system retrofits that do not require additional plumbing, venting, and electrical cost adders.
- In 2005, manufacturers estimated tankless market share up to 2 percent of annual shipments or 11 thousand units annually in California. However, appliance saturation studies in 2000 and 2005 suggest that California has a higher percentage of the annual U.S. tankless sales, perhaps 28 thousand units per year.
- The most critical aspects to maintaining tankless water heater performance are similar to those of storage water heaters and include water quality, temperature setting, proper sizing and selection of model, qualified installer and quality of installation, and proper maintenance.
- Market growth enhancers for gas tankless water heaters include higher efficiency than standard storage water heaters, continuous hot water, long projected life, lower energy costs, compact design, and rebates and incentive programs.
- Market growth inhibitors for gas tankless water heaters include first cost, installation cost-adders, required periodic maintenance by qualified professionals, and an immature market and service infrastructure.
- One tankless water heater manufacturer requires “manufacturer-sponsored training” as a pre-requisite for installation and servicing its equipment. Other manufacturers’

reference "qualified" tradesman in their installation manuals referring to licensed tradesman, knowledgeable in the National Fuel Gas Code and other gas-fired water heater safety features, and having a thorough understanding of the water heater installation.

- The first-cost premium of gas tankless water heaters diminishes when compared to higher efficient storage water heaters.
- Both tankless and storage water heater "Conditions of Warranty" are installation, operational, and application dependent. Deviations from the accepted conditions void the warranty. Warranty is not an indicator for equipment life.
- The improper use of a tankless water heater voids the warranty. It is important to verify that the intended application is covered by warranty. Some tankless water heater models are approved for use in residential domestic hot water use only and may not be approved for other applications such as solar preheat backup, high temperature booster use, hydronic heating, recirculation systems, and commercial applications.
- Gas tankless water heaters have different emission requirements than residential gas storage water heaters. Proposed 2012 tankless NO_x emission limits of 20 ppm (14ng/joule of heat output) are not as stringent as 2007 residential storage NO_x emission limits of 10 ng/joule of heat output.
- Un-optimized hot water distribution system designs and sub-par building practices that result in long un-insulated hot water pipe runs can reduce the perceived tankless water heater performance due to increased hot water delivery wait times, water usage and energy waste. Actual tankless water heater performance will be reduced from what is measured in the DOE's EF test if there are many hot water draws per day. Averages of 20-80 hot water draws per day have been recorded in recent hot water usage studies.

The recommendations from this task are as follows:

- Interviews with builders and plumbers suggest tankless water heaters used in combination space and water heating system application can provide possible installation cost savings. Research is needed to validate application-specific cost savings in using tankless over storage water heaters.
- Gas tankless water heaters claim a 20-year service life; however, the literature search was not able to validate this claim through published test results or studies. Claims of 20-year service life should be validated either through a third-party review of manufacturer's test data or accelerated life testing.
- A review of hot water usage studies found limited and inconclusive data. A more expansive analysis of household hot water usage representing current California demographics is needed to determine if tankless water heaters are able to meet minimal flow rates.
- The literature review did not find relevant information on commercial hot water distribution system design and commercial hot water use. Research is needed to understand how tankless technology can benefit commercial hot water use.

- Foodservice and kitchen facilities may incorporate recirculation systems due to time-critical water draws such as employee hand washing and dishwasher rinse cycles. Research is needed to understand the impact of different recirculation system strategies on the performance of tankless water heaters.
- Further investigation is needed to determine if plumbers view the tankless water heater market share as growing large enough to warrant the stocking of parts and replacement units to handle emergency calls, and the necessary installation and service training.
- Further investigation is required to determine how manufacturers, builders, and plumbers are considering tankless water heaters in the design of hot water distribution systems to minimize wait time and meet time-critical water draws.
- Efficiency standards in markets outside the U.S. may have a positive impact on the efficiency and performance of tankless water heaters sold in the U.S. Discussions with manufacturers are warranted to determine how efficiency standards development in China, efforts to reduce standby power for tankless water heaters in Australia, and changes in ratings methods and efficiency calculations of the European Union will influence products sold in the U.S.
- An analysis is needed to determine if, under similar water draws, a gas tankless water heater emits more or less NO_x than the 2007 SCAQMD requirements for gas storage water heater emissions.

A 2004 assessment of gas tankless water heaters by the Davis Energy Group for Pacific Gas & Electric captured some key elements to characterize the current and potential market in California. Assuming 9.9 million gas water heaters and an average service life of 13.5 years, the unbiased replacement opportunity for the California market is 738,977 units per year. With high EF compared to storage water heaters, a maximum of 0.92 versus a maximum of 0.67, the benefits in energy efficiency and reduced greenhouse gas emmissions to California are significant. First cost and installation cost hurdles need to be addressed.

3.0 Task 3: Commercial Gas Fryer for Foodservice

3.1. Introduction

One of the most common pieces of commercial equipment found in a foodservice kitchen is a deep fat fryer. Fryers are the original quick-service equipment because most products that are cooked are ready for consumption in only a few minutes. The most popular type of food cooked in this type of equipment is French fries, usually, two baskets at a time.

Over the past few years two issues arose associated with the use of gas-fired fryers: energy costs and trans-fat free oils. The increased costs of energy and the operation cost of fryers resulted in consumers approaching manufacturers and the gas industry for information about installing more efficient fryers. The other issue was the public's and foodservice industry's interest in eliminating the use of trans-fat oil in the frying process. Trans-fat, which are present in many deep-frying oils and lower good cholesterol while raising bad cholesterol levels, have become the subject of public scrutiny. Places like New York City and others have banned from being used in any public restaurant. With several other cities considering following suit, restaurant owners are looking to the foodservice equipment industry to provide technologies that can produce the same product that people have become accustomed to, while at the same time reducing operating costs and eliminating the trans-fats from the product. The main issue with using trans-fat free oils is not the availability; they are already widely available, but they cost more and have a different taste.

The objective of this task was to develop a gas fryer that reduced energy costs, improved performance and reduced oil consumption. Through the work completed in subtasks outlined below, a low oil volume fryer with advanced heat exchange was designed, tested, prototyped and field demonstrated (Cole and Johnson 2009a). The new fryer was tested to have a cooking energy efficiency of 60 percent, which would qualify for ENERGY STAR rating, a reduced oil requirement of 35 pounds from 50 pounds and a cooking capacity capable of meeting the demands of a typical restaurant.

3.2. Subtask 3.1: Specification Review

3.2.1. Introduction

Deep fat fryers are the original quick service piece of equipment as most products that are cooked in a fryer are done in just a few minutes. The most common food to be cooked in a fryer is fries. Commonly the fries are purchased frozen from a supplier. Portions are weighed out (typically 1.5 pounds per basket) and may be thawed prior to cooking. Fryers typically have the capacity to cook two baskets at a time. During the cooking process (about 3.5 minutes), fries will lose about 30 percent of their weight as they cook. They will also pick up about 5 percent of the precooked weight in oil from the fryer during cooking. The oil that is transferred to the food during cooking is called *dragout*.

3.2.2. Approach

To accomplish the objectives of this subtask, the following tasks were selected:

- Update the existing product baseline information with respect to energy utilization efficiency, cooking capacity, throughput, and anticipated cooking oil utilization based upon best practices for oil filtration, temperature control and food moisture management.
- Clarify the product specification with respect to market "must-haves" for deep fat fryers.
- Prepare *Energy-Efficient Gas Fryer Requirements* documenting key product characteristics based on the work performed in this subtask.

3.2.3. Outcomes

To meet the goals of the project, the new fryer must have an oil capacity of 35 pounds per vat or less (compared to the standard of 50 pounds), an energy efficiency that qualifies for ENERGY STAR™ and a cooking capacity of at least 60 pounds per hour of French fries. These requirements are detailed in the report submitted as the deliverable for this subtask, *Energy-Efficient Gas Fryer Requirements*. The report is located in the Appendix of the detailed report for this project (Cole and Johnson 2009a). The requirements for the fryer design developed in this task were used as the basis for the next subtask.

3.3. Subtask 3.2: Design Concepts Generation

3.3.1. Introduction

In this section of the report the total system and component designs are discussed. The design focused on meeting four objectives that would allow development of an efficient fryer that could successfully compete in the marketplace.

- Low oil volume, thus reducing oil replacement costs due to dragout and contamination, the design specification is 35 lbs compared to 50 lbs for current fryers.
- An integral filter system that would be easier to use and maintain than present discrete systems that require shutdown of the fryer.
- A design that does not allow oil temperature to exceed 425°F. Present gas fryers combustion systems create hot spots where oil temperatures may exceed 600°F, increasing potential for rapid oil degradation.
- A design that meets ENERGY STAR™ requirements in terms of efficiency

3.3.2. Approach

To accomplish the objectives of this subtask, the following tasks were selected:

- Develop and refine concepts that will meet the product specifications.
- Perform calculations to validate each approach.
- Assess approaches from the point of view of the manufacturer, services and end-user.

- Assess the merits and technical hurdles to determine the approaches that hold the most promise from a research and development perspective.
- Prepare a *Fryer Design Concepts Report* documenting the work performed in this subtask, including, but not limited to, an assessment and comparison of the various design approaches.

3.3.3. Outcomes

To successfully compete in the commercial foodservice marketplace, it was decided the new fryer would have a vat without tubes through it. Instead, the oil would be pumped through an external heat exchanger and filter to improve heat transfer efficiency, improve oil life and make cleaning of the fryer easier. The report this subtask, *Fryer Design Concepts Report* is located in the Appendix of the detailed report for this project (Cole and Johnson 2009a).

3.4. Subtask 3.3: Bench Assembly / Testing

3.4.1. Introduction

Traditional gas fired fryers transfer heat directly from combustion products to a fryer vat. Limitations of the traditional design include limits on combustion heat transfer efficiency, development of oil hot spots and thus short oil life, and large oil reservoirs. The overall objective of this project to develop a high efficiency gas fired fryer that maximizes cooking efficiency and reduces oil costs.

3.4.2. Approach

To accomplish the objectives of this subtask, the following tasks were selected:

- Develop a *Fryer Bench Testing Plan* documenting one or more design concepts to be bench-tested, along with test procedures and success criteria.
- Fabricate bench test modules of the burner / heat exchanger subsystem and the pump / filter subsystem.
- Assemble bench test modules of the burner / heat exchanger subsystem and the pump / filter subsystem.
- Test the modules for emissions, efficiency and robustness within the anticipated environmental conditions, as well as, under abnormal conditions prescribed by known standards.
- Prepare a Draft *Fryer Bench Testing Report* documenting the results of the bench tests performed in this subtask.

3.4.3. Outcomes

A low oil volume high efficiency gas fired fryer was designed, constructed and tested.

Results from cook tests with breaded chicken frying tests included:

- Combustion efficiency exceeded 75 percent
- Volume and quality of cooked chicken was excellent
- Extended oil life was not shown

This set of testing did not show extended oil life, however it was believed this can be achieved in the final design by modifying the filter design in the unit.

Results from cook tests with French fry tests included:

- Temperature cooking curve and cooked weights were within the goal of the project and ASTM standard.
- Oil temperature drop (from 360 to 315°F) criterion was met
- Preliminary ASTM efficiency was up to 57.8 percent and production rate of 66.3 lbs/hr

These outcomes are detailed in the reports submitted as the deliverables for this subtask (Cole and Johnson 2009a):

- *Fryer Bench Testing Plan*
- Draft *Fryer Bench Testing Report*
- 1st CPR Report
- Final *Fryer Bench Testing Report*

The reports are located in the Appendix of the detailed report for this project (Cole and Johnson 2009a).

3.5. Subtask 3.4: Design Documentation

3.5.1. Introduction

The objectives of this task were to create a *Fryer Functional Specification Report* to provide design details and estimated cost.

3.5.2. Approach

To accomplish the objectives of this subtask, the following tasks were selected:

- Create a *Fryer Functional Specification Report* including, but not limited to, the following information:
  - Document with cutaway views and system explanatory information
  - Projected cost-to-customer information for the new fryer design

3.5.3. Outcomes

A full specification sheet for a new low oil fryer was developed and entitled, *Fryer Functional Specification Report*. The specification sheet is given in the detailed report for this project (Cole and Johnson 2009a).

3.6. Subtask 3.5: Computational Fluid Dynamics Modeling and Analysis

3.6.1. Introduction

The objective of this subtask was to develop a Computational Fluid Dynamics (CFD) model for the fryer and conduct an analysis of its performance.

3.6.2. Approach

To accomplish the objectives of this subtask, the following tasks were selected:

- Perform a CFD analysis of the fryer including both heat transfer and combustion analysis. This analysis will be based on the design documentation from subtask 3.4 and the preliminary testing performed on the bench assemblies from subtask 3.3.
- Prepare a Fryer CFD Analysis Report documenting the numerical and graphical CFD analysis and identifying design refinements prior to fabrication and assembly of prototype units.

3.6.3. Outcomes

A CFD study for a proposed design for a fryer heat exchanger was conducted to determine the temperature rise in the oil, as well as, all flow and thermal characteristics of the design. Given the current coil and housing configuration and an oil inlet temperature of 340 °F, the oil outlet temperature was observed to be 399.2 °F. The results were evaluated and used to design the heat exchanger. The results are detailed in the report *Fryer CFD Analysis Report* and given in the detailed report for this project.

3.7. Subtask 3.6: Prototype Build / Test / Refinement

3.7.1. Introduction

The objectives of this subtask were to build, test, and refine a fryer prototype build in accordance with the functional specification and the CFD modeling results.

3.7.2. Approach

To accomplish the objectives of this subtask, the following tasks were selected:

- Fabricate and construct a prototype fryer in order to validate the achievement of the performance goals established in Task 3.2.
- Test the fryer according to the ANSI standard for Deep Fat Fryers and through food cooking tests following the ASTM standard to characterize efficiency and capacity.
- Prepare a *Fryer ANSI/ASTM Test Report* summarizing the results of the prototype fryer tests conducted in this subtask.

3.7.3. Outcomes

Testing with the new low oil volume fryer showed improved oil quality, cooking efficiency of 60 percent and production rate of 93 pounds per hour of French fries. The results are detailed in the report *Fryer ANSI/ASTM Test Report* and given in the detailed report for this project.

3.8. Subtask 3.7: California Market Introduction Plan

3.8.1. Introduction

The objective of this task was to develop a market introduction plan for the new fryer design for the state of California.

3.8.2. Approach

To accomplish the objectives of this subtask, the following task was selected:

- Develop a *California Market Introduction Plan* outlining activities that the Key Partner will use with its sales distribution force in California to introduce the new gas fryer product.
- Develop the *California Market Introduction Plan*.

3.8.3. Outcomes

Eight sets of Marketing Education Materials and Manufacturer Marketing Materials were developed to help with the market introduction of the new low oil volume fryer into the California commercial foodservice market. These materials are given in the detailed in the report entitled *California Market Introduction Plan* and given in the Appendix for the detailed report for this project. The fryer was also displayed at several foodservice industry shows including North American Foodservice Equipment Manufacturers and National Restaurant Association shows.

3.9. Commercial Gas Fryer Conclusions and Recommendations

The goal of this task was to develop a gas fryer that reduces energy costs, improves performance and reduces oil consumption. Through the work completed in subtasks, a low oil volume fryer with advanced heat exchange was designed, tested, prototype and field demonstrated. The new fryer was tested to have a cooking energy efficiency of 60 percent, which would qualify for ENERGY STAR™ rating, a reduced oil requirement of 35 pounds from 50 pounds and a cooking capacity capable of meeting the demand of a typical restaurant.

4.0 Task 4: Commercial Underfired Charbroiler for Foodservice

4.1. Introduction

Commercial charbroilers are found in about 30 percent of all U.S. restaurants, and are primarily used to grill meats. Charbroilers are classified as either underfired or over-fired. On an underfired charbroiler, the top surface is a grate over a heat source. In an over-fired charbroiler, food is placed on a grate with heat applied from above. Charbroilers require preheating of the grates to provide the signature grill marks. As a result, often the charbroiler is turned on well in advance to ensure that the grate will be hot enough. In addition, the charbroiler is sometimes left on for extended periods when few customers are in the restaurant. Along with the energy that the charbroiler itself consumes, it places a tremendous load on HVAC systems, requiring high exhaust flow rates and introducing a significant amount of heat into the surrounding space. However, a broiler's unique "char broiled" taste ensures it will continue to have widespread use throughout the food service industry.

Previous research into the performance of charbroilers is very limited compared to other gas-fired appliances. One of the studies by the FSTC showed charbroilers to be relatively inefficient. Results from cooking tests on typical 3-foot broilers indicate an energy efficiency of 30 percent to 35 percent for a gas broiler and 40 percent to 45 percent for an electric broiler. However, in typical real-world usage, partial loading conditions are the norm, and energy efficiency drops to around 6 percent for a gas broiler and 15 percent for an electric broiler. If an entire production day is analyzed, the period of idle energy usage is significant, and light load cooking efficiencies are representative of real world broiler efficiency. For example, a gas-underfired broiler used to cook 100 lb. of food over an 8-hour period consumed 600 kBtu of energy (FSTC Production Test Kitchen data). Using the estimate of 300 Btu per lb. of food cooked, the total energy actually delivered to the food product over the 8-hour period would be approximately 30 kBtu. This translates to a real-world cooking energy efficiency of only 5 percent.

Despite the known operational issues associated with charbroilers, very little research time and money has been spent toward improving their performance. Despite the higher operational costs, charbroiler manufacturers have been hesitant to change the design of the appliances to improve their performance over concerns of negatively affecting the taste and look of the end product. As emphasized to GTI by different manufacturers, the charbroiler provides a unique look and flavor to cooked products that must be maintained to ensure the appliance's appeal to their customers. However, changes in the cost structure of natural gas and new emissions requirements have increased the industries' interest in improving the performance of charbroilers.

The objective of this task was to improve the real-world cooking efficiency of charbroilers above 5 percent, reduce the heat gain to the space proportionally, and not impact the cooking characteristics of the device or change the look or flavor of the cooked products. This objective was to be addressed by designing an advanced charbroiler with retractable hood and thermostat while maintaining the unique cooking characteristics of the charbroiler.

To accomplish the goals of this project, the work was divided up into the following subtasks with the subtask deliverables listed with their respective tasks:

- Subtask 4.1 Specification Review and Redesign
    - Requirements for the design of the new underfired charbroiler
- Subtask 4.2 Prototype Construction
    - Underfired Charbroiler Design Report
- Subtask 4.3 Performance Testing
    - Charbroiler ASTM Test Report
- Subtask 4.4 Demonstration
    - Report "Demonstration of Underfired Gas Charbroiler"

Each work completed and deliverables for each subtask to this project is detailed in following sections.

4.2. Subtask 4.1: Specification Review and Redesign

4.2.1. Introduction

The commercial underfired broiler is a top candidate for performance enhancement. Used in many food service operations, broilers are notoriously inefficient–often operating at or near full input at all times. They place a tremendous load on HVAC systems, requiring high exhaust flow rates and introducing a significant amount of heat into the surrounding space. However, a broiler provides a signature "char broiled" taste that cannot be achieved through other cooking processes and so they have, and will remain to have, widespread use throughout the food service industry. Since broilers are relatively low-tech, the opportunity to provide significant energy savings through improved broiler design is real.

The FSTC developed a Standard Test Method for Performance of Underfired Broilers (ASTM Designation F 1695-96); to allow the evaluation of energy performance of underfired broilers. Results from cooking tests on typical 3-foot broilers indicate an energy efficiency of 30 perncet to 35 percent for a gas broiler and 40 percent to 45 percent for an electric broiler. However, in typical real-world usage, partial loading conditions are the norm, and energy efficiency drops to around 6 percent for a gas broiler and 15 percent for an electric broiler. If an entire production day is analyzed, the period of idle energy usage is significant, and light load cooking efficiencies are representative of real world broiler efficiency.

Based on data from NAFEM, there are about 250,000 underfired charbroilers in the US and Canada, with about 20,000 in California. Testing of a typical gas fired charbroiler operating 12 hours per day showed an energy consumption of about 250,000 kBtu per year. A 20 percent improvement in energy efficiency results in savings of about 500 therms/yr per charbroiler. If 20 percent of the existing broilers in California were replaced with the higher efficiency units, about 2 million therms/yr would be saved in California alone.

4.2.2. Approach

To accomplish the objectives of this subtask, the following elements were used in the approach:

- Review with the manufacturer the current design for the prototype underfired charbroiler and suggest design changes to improve the efficiency and operation of the unit.
- Clarify the product specification with respect to market "must-haves" for charbroilers.
- Prepare *Requirements for the Design of the New Underfired Charbroiler* documenting key product characteristics based on the work performed in this subtask.

4.2.3. Outcomes

After reviewing existing charbroiler designs with industry experts and manufacturers, for the underfired charbroiler developed during this project, the "must haves" in terms of charbroiler design and performance were:

- Maintain the unique flavor and texture to cooked food provided by existing charbroilers
- Improved cooking efficiency by at least 50 percent
- Improved operational characteristics for the chefs including comfort by reducing ambient heat gain while operating the unit

The identified "must haves" served as guidance for the project and are the deliverable for this subtask, *Requirements for the Design of the New Underfired Charbroiler* (Cole and Johnson 2009b).

4.3. Subtask 4.2: Prototype Construction

4.3.1. Introduction

A typical underfired charbroiler, as shown in Figure 1, has a burner under a metal grate on which the food is prepared. The unit is manually controlled by the knobs on the front panel.

Figure 1. Typical Underfired Charbroiler
Source: Gas Technology Institute

The prototype unit (Figure 2) was constructed by a charbroiler manufacturer based on drawings provided by GTI.

Figure 2. Advanced Charbroiler Design with the Hood Open and Closed
Photo Credit: Gas Technology Institute

A temperature probe is mounted under the stationary section of the hood and is connected to a thermostat that regulates the temperature of the unit. The hood works with the thermostat controls to improve the efficiency in terms of fuel usage of the broiler. When the hood is closed, the temperature inside the broiler rises rapidly until the thermostat shuts off the burners at the cooking set point. The energy savings comes from this modulating of the burner. Other charbroilers are not thermostatically controlled. When the burners are on, even when food is not on the cooking grates, the unit is firing at maximum capacity. The charbroiler in this project can cook similar to other charbroilers with the hood up at maximum burner firing rate, but closing the hood during cooking or idle periods allows keeping the charbroiler at a ready to use temperature. This saves time associated with warming up the charbroiler. Because charbroilers can take several minutes to reach cooking temperatures, operators generally leave them on during idle periods. The hood also creates a passage at the top that a catalyst substrate similar to the one in Figure 3 could be mounted. In order to catalyze the grease and particulates, the catalyst would have to be heated by either the flue gases or an extra heater. However; this type of catalyst has been shown in other appliances as being effective in removing grease and particulate emissions.

Figure 3. Charbroiler Catalyst
Photo Credit: Gas Technology Institute

4.3.2. Approach

To accomplish the objectives of this subtask, the following elements were used in the approach:

- Review design drawing with manufacturer
- Assist the manufacturer with the fabrication and construction of two prototype charbroilers in order to achieve the performance goals established in Subtask 4.1.

4.3.3. Outcomes

- Based on drawing developed by GTI, a prototype underfired charbroiler was built by a charbroiler manufacturer with a hood and thermostat. A temperature probe is mounted under the stationary section of the hood and is connected to a thermostat which regulates the temperature of the unit. The hood works with the thermostat controls to improve the efficiency in terms of fuel usage of the broiler. The deliverable for this subtask, *Underfired Charbroiler Design Report*, is included in the Task report (Cole and Johnson 2009b).

4.4. Subtask 4.3: Performance Testing

4.4.1. Introduction

The prototype unit was tested by GTI and FSTC using both ceramic and metal fiber burners, Figure 4, to determine the cooking efficiency of the different designs using standard ASTM test methods.

Figure 4. Ceramic and Metal Fiber Burners
Photo Credit: Gas Technology Institute

The standard ASTM cooking test used 24, 1/3-lb, 80/20 hamburger patties that were stabilized to 40°F in a refrigerator. Hamburger patty cook time was determined to give finished patties an average final temperature of 170°F. A full test run consisted of 2 stabilization loads followed by 3 test loads, with 1-minute unload/scrape time between loads. This test was repeated two additional times to give three data points.

Figure 5. Cook Testing of Charbroiler
Photo Credit: Gas Technology Institute

4.4.2. Approach

The following tests were completed by FSTC.

Royal Range Advanced Underfired Broiler with Ceramic Burners

Input Rate Test- The test broiler input rate was measured with all controls set to full input. The energy rate was measured at 88,500 Btu/h.

Temperature Distribution- Broiler grate temperature was measured using ¼-inch thick, 5¼-inch diameter steel disks with a thermocouple tack-welded to the center of one side. The test was conducted with 24 steel disks, evenly distributed across the grate, the controls set to full input, and the lid open. The burners did not cycle during this test. The resulting temperatures were as follows in degrees Fahrenheit:

581	516	558	554	524	588
672	557	581	596	544	664
676	583	612	591	579	673
549	548	565	535	527	596

(Front Side)

- Maximum Temperature- 676°F
- Minimum Temperature- 516°F
- Difference- 160°F

Preheat test- Using 3 steel disks (1 per linear foot), and beginning from a standing (room temperature) start, time and energy were monitored while the broiler preheated. Preheat was judged complete when the last disk reached a temperature of 500°F. The burners did not cycle off during the lid up or the lid down preheat test.

- Lid Up - Preheat time of 16.2 min and energy usage of 25,600 Btu.
- Lid Down - Preheat time of 12.0 min and energy usage of 19,180 Btu.

Cooking Energy Efficiency- Using the steel disks, the broiler controls were adjusted so the disks were as close to 600°F as possible. After removing the disks, the broiler was stabilized for one hour. The cooking tests used 24, 1/3-lb, 80/20 hamburger patties that were stabilized to 40°F in a refrigerator. Hamburger patty cook time was determined to give finished patties an average final temperature of 170°F. A full test run consisted of 2 stabilization loads followed by 3 test loads, with 1-minute unload/scrape time between loads. This test was repeated two additional times to give three data points, and the energy efficiency was calculated, according to the following (simplified) equation:

Energy Efficiency = Energy Imparted to Food/Energy Consumed by Broiler

With the lid up and the thermostat adjusted to its maximum setting of 500°F, the cook time was 6.75 minutes. The burners occasionally cycled off for a short period when the patties were removed from the broiler. Energy efficiency was 44.7 percent ± 0.7 percent. The cooking energy rate was 60,830 Btu/h, and the production capacity was 62.7 lbs/h ± 0.6 lbs/h.

With the lid down, the cook time shortened to 6 minutes. The burners cycled off slightly longer than during the lid up test, typically when the burgers were removed. Energy efficiency was 52.9 percent ± 1.3 percent. The cooking energy rate was 57,570 Btu/h, and the production capacity was 69.5 lbs/h ± 0.1 lbs/h.

Idle Energy Rate- The broiler was monitored while unloaded at the 600°F calibration used for the cooking tests. With the lid up and the thermostat adjusted to its maximum setting of 500°F, the idle energy rate was 65,110 Btu/h. The burners did not cycle off during this test.

With the lid down, the burners cycled on and off. The lid-down idle energy rate was 53,860 Btu/h.

A third test was conducted with the lid down and the thermostat set to 350°F. The energy rate for this test was 34,380 Btu/h.

Pilot Energy Rate- This simply measured the energy consumption of the standing pilots, with all controls set to "off". The pilots were measured at 2,960 Btu/h.

Electric Energy Consumption- Whenever the broiler is turned on by the main on/off switch, it consumes a small, constant amount of electricity- about 4.5 Watts.

Advanced Underfired Broiler with Metal Burners

Input Rate Test- The test broiler input rate was measured with all controls set to full input. The energy rate was measured at 88,500 Btu/h.

Temperature Distribution- Broiler grate temperature was measured using ¼-inch thick, 5¼-inch diameter steel disks with a thermocouple tack-welded to the center of one side. The test was conducted with 24 steel disks, evenly distributed across the grate, the controls set to full input, and the lid open. The resulting temperatures were as follows in degrees Fahrenheit:

553	480	518	519	542	615
653	527	572	559	592	657
697	552	567	571	629	682
585	536	520	521	576	620

(Front Side)

- Maximum Temperature- 697°F
- Minimum Temperature- 480°F

- Difference- 217°F

Preheat test- Using 3 steel disks (1 per linear foot), and beginning from a standing (room temperature) start, time and energy were monitored while the broiler preheated. Preheat was judged complete when the last disk reached a temperature of 500°F.

- Lid Up - Preheat time of 20.5 min and energy usage of 29,190 Btu.
- Lid Down - Preheat time of 23.6 min and energy usage of 24,631 Btu. With the lid down, the burners began cycling before the disks reached 500°F, resulting in the longer preheat time.

Cooking Energy Efficiency- Using the steel disks, the broiler controls were adjusted so the disks were as close to 600°F as possible. After removing the disks, the broiler was stabilized for one hour. The cooking tests used 24, 1/3-lb, 80/20 hamburger patties that were stabilized to 40°F in a refrigerator. Hamburger patty cook time was determined to give finished patties an average final temperature of 170°F. A full test run consisted of 2 stabilization loads followed by 3 test loads, with 1-minute unload/scrape time between loads. This test was repeated two additional times to give three data points, and the energy efficiency was calculated, according to the following (simplified) equation:

Energy Efficiency = Energy Imparted to Food/Energy Consumed by Broiler

With the lid up and the thermostat adjusted to its maximum setting of 500°F, the cook time was 6.75 minutes. The burners did not cycle during this test. Energy efficiency was 38.9 percent ± 0.7 percent. The cooking energy rate was 67,500 Btu/h, and the production capacity was 62.9 lbs/h ± 0.1 lbs/h.

With the lid down, results became difficult to determine. Flare-up when turning or removing patties cycled the burners off for varying lengths of time. Sometimes the burners would cycle off for periods of several minutes. This led to a large variance in the amount of gas used and the weight loss of the patties from load to load. More consistent cycling or a modified test procedure would be necessary to produce meaningful results for this test.

Idle Energy Rate- The broiler was monitored while unloaded at the 600°F calibration used for the cooking tests. With the lid up and the thermostat adjusted to its maximum setting of 500°F, the idle energy rate was 67,170 Btu/h. The burners did not cycle off during this test.

With the lid down, the burners cycled on and off. The lid-down idle energy rate was 43,020 Btu/h.

A third test was conducted with the lid down and the thermostat set to 350°. The energy rate for this test was 20,050 Btu/h.

Pilot Energy Rate- This simply measured the energy consumption of the standing pilots, with all controls set to “off”. The pilots were measured at 2,800 Btu/h.

Electric Energy Consumption- Whenever the broiler is turned on by the main on/off switch, it consumes a small, constant amount of electricity- about 4.5 Watts.

4.4.3. Outcomes

Results were similar for the broilers with the ceramic and metal burners, except for one issue with the cooking efficiency results. Both showed maximum firing rates and temperature differences across the grates typical for underfired charbroilers. Improvements in performance were evident in the preheat, cooking and idle efficiencies. The preheat for the ceramic burner charbroiler was four minutes faster with the hood closed using less energy (19,000 vs. 25,600 Btu). For the metal fiber burner, less energy was used (24,600 vs. 29,000 Btu), but the preheat was slightly larger with the hood down because the burner began to cycle.

Cooking efficiencies were shown to be higher than a typical charbroiler and improved when the hood was closed during cooking. For the ceramic burner, the cooking efficiency was 45 percent for the lid open and 52 percent for the lid closed, both more than 50 percent better than a typical charbroiler. The metal fiber burner was 39 percent for the lid up. For the testing with the lid down, the data varied because of the cycling of the burner in association with the time of the testing. As noted by FSTC, sometimes the burners would cycle off for periods of several minutes. This led to a large variance in the amount of gas used and the weight loss of the patties from load to load. More consistent cycling or a modified test procedure would be necessary to produce meaningful results for this test.

Idle energy tests were conducted with the thermostat set to 500 °F. The ceramic burner charbroiler used 65,000 Btu with the lid open and 53,800 Btu with the lid closed. Even better results were recorded for the metal fiber burner with 67,000 Btu for the lid open and 43,000 with the lid closed.

The testing showed that as currently configured, the advanced underfired charbroiler with the hood and thermostat would easily save 50 percent of the energy consumed by the typical charbroilers currently on the market. Optimization of the burner design and placement of the temperature probe could further improve the efficiency.

4.5. Subtask 4.4: Demonstration

4.5.1. Introduction

The objective of this subtask was to evaluate the cooking qualities of the improved charbroiler against the standards expected by an experienced operator. To confirm the latter goals, the charbroiler was evaluated by two foodservice professions: the head chef at the café at GTI and the chef at the cafeteria at the San Ramon Valley Conference Center.

4.5.2. Approach

- Determine and prepare two test site locations.
- Collection data about the usage and performance of the prototype charbroiler from the foodservice operations.

4.5.3. Outcomes

The chef at GTI commented on benefits of being able to close the hood and reduce the amount of heat being exposed to the user or the other persons working in the kitchen. He also gave positive feedback on the taste and appearance of the food cooked on the broiler, as shown in in Figure 6.

Figure 6. Demonstration of Charbroiler at GTI
Photo Credit: Gas Technology Institute

The unit installed at the San Ramon Valley Conference Center, Figure 7, was used to prepare between 100 and 300 meals per day for at least two weeks. The unit was able to cook the products typically prepared using their other charbroiler. The staff commented that some time was required to "learn" the cooking characteristics of the broiler, especially, compared to the broiler this one replaced. The chefs did prefer cooking with the lid down except when during busy times. However, some issues where observed with the broiler concerning the settings on the burner firing rate and thermostat. The thermostat was set on high with the burners set to 75 percent of maximum capacity. At these settings, the burners were not cycling, as occurred during testing at GTI, and the cook times were a little longer than for the replaced broiler. The chefs did note the preheat time for the broiler with the lid was less than 10 minutes compared to 30 minutes for the old broiler.

Data for the energy use showed the average gas consumption for the new charbroiler was 62 ft^3 per hour compared to 84 ft^3 for the old broiler. This energy savings rate would save about 640 therms of gas per year, assuming 12 hours of operation per day, 5 days per week for 52 weeks per year. The difference the hourly energy consumption of the two units is charted in Figure 8 and Figure 9. Figure 8 for the Advanced Broiler shows an average energy rate of approximately 60 kBtu/hr for a typical day of operation. For a standard broiler, the average shown in Figure 9 was about 90 kBtu/hr for a day with the same hours of broiler use as in Figure 8.

Results from the demonstration testing and performance data were incorporated into a brochure prepared by Magus Consulting. The brochure given in the Appendix (Cole and Johnson 2009b), *Charbroiler Brochure,* will be used by Royal Range in the next phase of the charbroiler work for marketing the new design.

Figure 7. Advanced Broiler Installed in Cafeteria Cook Line
Photo Cedit: Gas Technology Institute

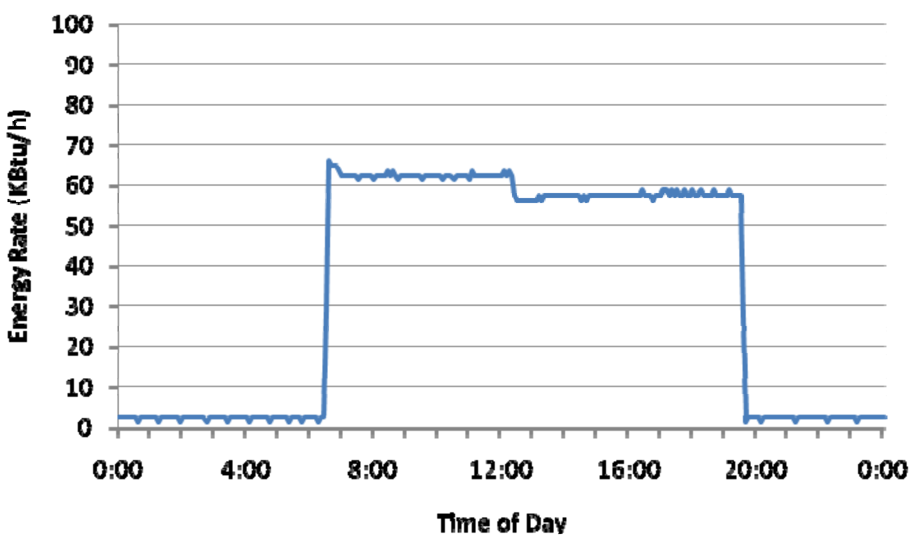

Figure 8. Advanced Broiler Energy Use for a Typical Day
Source: Gas Technology Institute

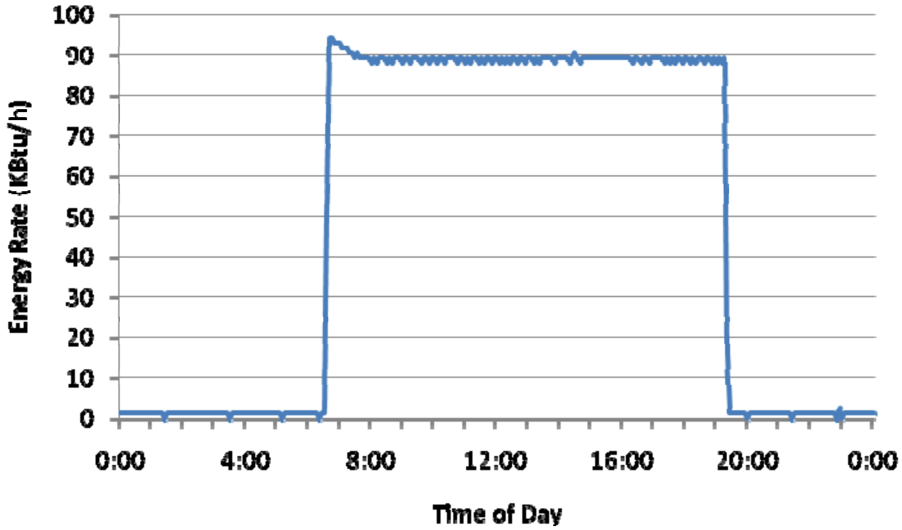

Figure 9. Standard Broiler Energy Use for a Typical Day
Source: Gas Technology Institute

Prototype underfired charbroilers were evaluated at chefs at both GTI and San Ramon Valley Conference Center.

The chef at GTI commented on benefits of being able to close the hood and reduce the amount of heat being exposed to the user or the other persons working in the kitchen. He also gave positive feedback on the taste and appearance of the food cooked on the broiler.

The prototype unit was also installed at the cafeteria at the San Ramon Valley Conference Center in San Ramon, CA and used to prepare meals for at least two weeks. The unit was able to cook the products typically prepared using their other charbroiler and received positive comments when asked by staff from FSTC about it performance.

4.6. Commercial Underfired Charbroiler Conclusions and Recommendations

The overall goal of this task was to address both the efficiency and heat gain issues by designing an advanced charbroiler with retractable hood and thermostat while maintaining the unique cooking characteristics of the charbroiler. The results of this task showed that as currently configured, the advanced underfired charbroiler with the hood and thermostat would easily save 50 percent more energy than the typical charbroilers currently on the market. The design also allows for installation of a catalyst to reduce grease and particulate emissions. The unit was also tested by two chefs who were both pleased and impressed with the unit performance and cooking characteristics.

Based on the results of this task, the project team recommends working with Royal Range and gas utilities in California to conduct field tests for the new advanced broiler to quantify the energy savings and cooking benefits of the new design. Results would be used to assist with commercialization of the unit.

Quantitative and qualitative benefits of this project accrue primarily to California owners of establishments in the form of energy savings, reduced CO_2 emissions and improved quality for food product preparation. Specifically, commercial foodservice providers will be able to save on the cost of preparing food products for their customers while maintaining the quality their customers have become accustomed to. Also comfort levels for the employees will be improved because the volume of waste heat that flows into the cooking area increasing the ambient temperature is reduced.

Quantitative benefits are summarized below:

	Population	Base Efficiency (%)	New Efficiency (%)	Load Savings (10^6 Therms)	CO2 Emissions Savings (Metric Tons)
Underfired	**42,000**	**28**	**45**	**15.6**	**83,000**
Over-fired	**5,300**	**22**	**45**	**1.5**	**5,600**

Table 2. Quantitative benefits of the project

Source: Gas Technology Institute

Royal Range has indicated that they will commercialize the new charbroiler design. Although it is not yet in the market, the basis for the assumed market penetration of the energy efficient appliances was research conducted by FNi. We based the savings potential on a 25 percent penetration of underfired broilers and a 20 percent penetration for over-fired broilers.

5.0 Task 5: Commercial Over-fired Broilers

5.1. Introduction

Broilers are the central appliance in many food service operations, both large and small. Depending on size and design, broilers are used for anything from melting cheese to cooking large cuts of meat in vast quantities. Broilers are used to cook steak, fish, chicken, shish kebabs and seafood as well as to brown food such as casseroles, to finish au gratin dishes and meringues, to reheat plated food and to melt cheese toppings. The desirable characteristics of broiling are striping (the marks created by the hot grill or "grid"), browning, searing, charring, crisping, and with cheese, melting. Depending on the desired final product, some cooking applications are only appropriate for certain types of broilers.

Over-fired broilers are typically used in high-volume institutional kitchens, hotels or steakhouses. Food is cooked in a broiler cavity that resembles an oven without a door. The heat source may be gas radiant burners, infrared burners or electric elements mounted in the top of the cavity. Food is placed on top of a grid, which can usually be adjusted to vary the distance between the food and the heat source. Cooking is accomplished by radiant heat from above the food and heat conducted from the grid to the food. Below the food there is a grease pan to catch drippings.

Figure 10. Over-fired broiler

Source: Gas Technology Institute

Over-fired broilers do not use any type of controls with feedback, such as thermostats or timers to control the cooking process, and so demand the attention and experience of the operator. The amount of heat transferred to the food is manually adjusted by regulating the energy input to the broiler and changing the placement of the grid, or the food on the grid. Operators become familiar with hot and cold areas on the grid through experience, and these may be varied by adjusting the height of the grid in over-fired broilers and by slanting the grid in some underfired charbroilers. Input is regulated manually with one or two controls on over-fired broilers and often one control per burner on charbroilers (typically 2 burners per foot of broiler width).

Due to their manual control, broilers usually idle at full input so that they are ready to cook the instant they are needed. This, combined with their inherently low efficiency, makes broilers one of the most energy-intensive appliances in commercial kitchens.

Used in many food service operations, over-fired broilers provide easy access, less heat gain to the kitchen than open charbroilers, a seared product appearance and a "char broiled" taste that cannot be achieved through other cooking processes. However, broilers have a lower efficiency and higher emissions compared to other foodservice equipment.

The objective of the commercial over-fired broiler project in task 5 was to improve the design of the gas-fired over-fired broiler to reduce energy consumption by 25 percent, and reduce heat lost to the space. This objective is to be met without impacting the quality, the cooking process, or the look of the wide variety of products that are cooked with gas-fired over-fired broilers in commercial kitchens.

This development research benefits public interest in two ways: 1) the energy savings benefits accrue directly to California citizens in the form or improved system efficiency, and 2) the environmental benefits of the reduced emissions. Currently about 170,000 gas over-fired broilers are in use in the foodservice industry, with approximately 20 percent of these are in California. The redesign broiler could result in a 25 percent reduction of the 1100 therms/yr that typical broiler uses. If 10 percent of the existing units are replaced with the new broiler, 935,000 therms/yr would be saved in California alone.

5.2. Subtask 5.1 Kickoff Meeting and Specification Review

5.2.1. Introduction

GTI contacted Vulcan-Hart, a major manufacturer of over-fired broilers, about participating in this effort. A project kickoff meeting was held at the Vulcan-Hart manufacturing facility in Baltimore, Maryland. In attendance were:

- Chris Bauermann Vulcan General Manager for Heavy Duty Cooking
- Chuck Czajka Vulcan Senior Engineer
- Tim Cole Gas Technology Institute

At the kickoff meeting, discussions were conducted around Vulcan Hart's needs for a new design over-fired charbroiler. California's needs and the goals of the California Energy Commission and their buildings initiatives were also discussed.

5.2.2. Approach

The outcome of that meeting was that the team would pursue two design alternatives, one to reduce the emissions from the charbroiler by incorporating a catalyst into the broiler and another to replace the existing burner designs with a new burner system altogether.

Catalyst incorporation into broiler design

BASF Catalysts LLC had worked previously with the manufacturers of chain-driven charbroilers to incorporate a catalytic cleanup system into the broiler. The catalyst has proven effective in reducing both particulate matter (PM) grease emissions and Volatile Organic Compounds (VOCs) as shown in Figure 11. Additionally, when the catalyst was incorporated into the chain-driven broiler, the energy efficiency of the unit improved. Both emission control and energy efficiency were very important product improvement objectives for the manufacturing partner. Specifications for a catalyst system discussed at the kickoff were:

- Reduce emissions from an over-fired broiler to a level similar to the results from the chain-driven charbroiler.
- No increase in overall footprint from standard products.
- The double deck broiler is quite tall and if a catalyst is placed on the top, it must fit within the confines of a normal height commercial foodservice ventilation hood.
- Energy efficiency improvement of at least 20 percent over standard products.
- No adverse change in cooking uniformity across the deck.
- No adverse effect on the cooked products.
- Minimize the cost adder for a catalyst system.

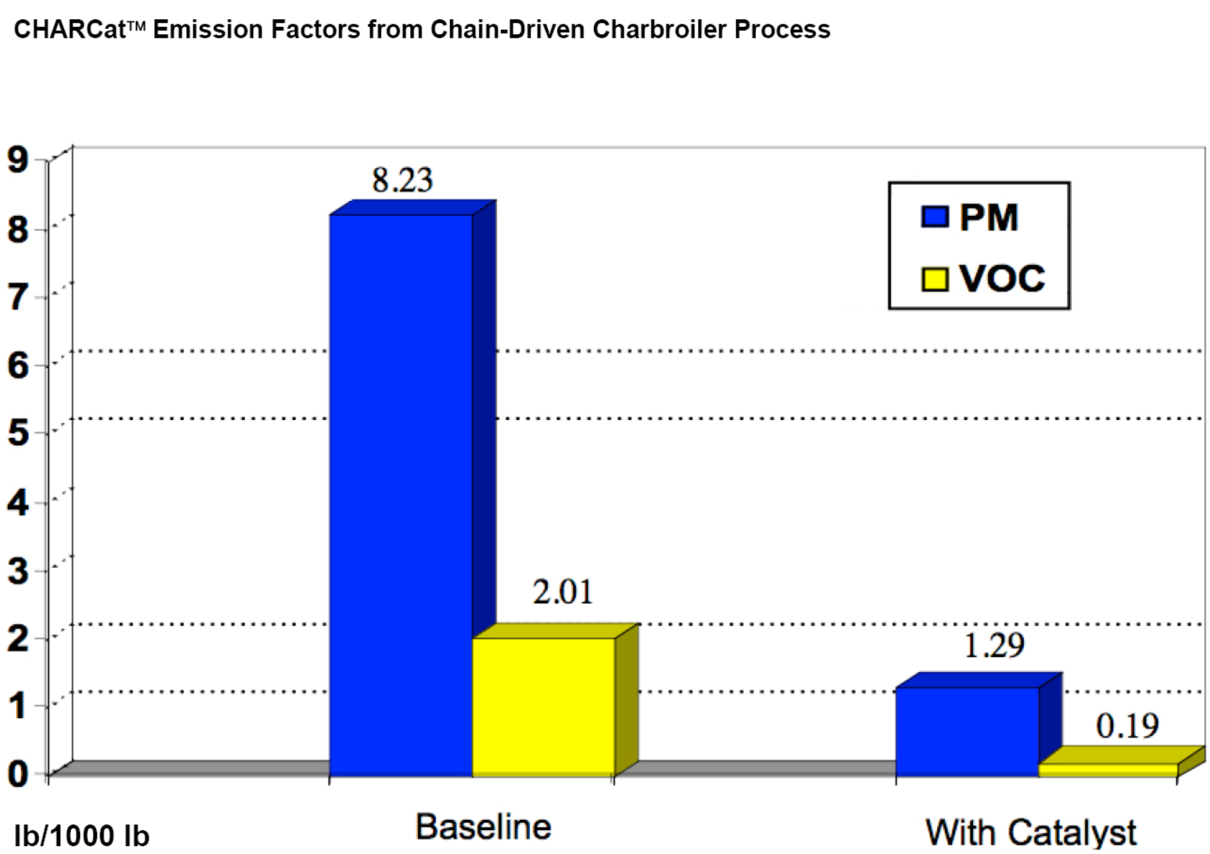

Figure 11. BASF emission reduction from use of catalyst

Source: Gas Technology Institute

New Burner System Design

The current burner systems that are in place in standard over-fired broilers are very mature designs. Some burners are blue flame burners that heat radiant emitting material that in turn heats the food, while other broilers have infrared burner systems that radiate directly to the food. The ignition temperature of natural gas is approximately 1200 °F. The flame will extinguish itself if the temperature falls below the ignition temperature.

Figure 12 shows a typical test result from the ASTM test procedure applied to an over-fired broiler with an infrared burner. Key among the results shown are the Cooking Energy Efficiency of 22.5 percent and the Temperature Uniformity which varied from 575°F -792°F. Specifications for a catalyst system discussed at the kickoff were:

- No increase in overall footprint from standard products.
- Energy efficiency improvement of at least 20% over standard products.
- Improvement in cooking uniformity across the deck.
- No adverse effect on the cooked products.

Energy Input Rate:

Measured (Btu/h): 100,000
Rated (Btu/h): 99,000
Difference (%): 1.0
Electric Rate (kW): n/a

Preheat:

(Max input, to 700°F as measured by steel disks):

Preheat Time (min): 34.8
Energy Consumption (Btu): 53,575

Cooking Energy Efficiency (Chicken Breasts):

Temperature calibration (°F): 800
Number of Breasts: 30
Cook Time (min): 9.2
Cooking Energy Rate (Btu/h): 85,193
Cooking Energy Efficiency (%): 22.5 ± 1.8
Production Rate (lb/h): 51.0 ± 1.6
Energy to Food (Btu/lb): 376

Temperature Uniformity (800°F Calibration):

651	705	706	652
724	768	783	717
731	792	792	746
704	744	742	722
575	617	617	586

Front

Figure 12. ASTM test results from a typical infared over-fired broiler

Source: Gas Technology Institute

5.2.3. Outcomes

The work performed in this subtask provided the basis for the next subtask, Design Concepts Generation. Both the catalyst and burner concepts were pursued.

5.3. Subtask 5.2 Design Concepts Generation

5.3.1. Introduction

The objective of this subtask was to generate one or more new design concepts for the commercial over-fired broiler.

5.3.2. Approach

Following the development of the design specifications in subtask 5.1, GTI began working with BASF to develop a design concept for the catalyst system. Vulcan-Hart engineers had discussed a potential new burner system design with a fabricator in New England. They took the lead on the generation of that concept.

After a few months of unsuccessful negotiation with a New England fabricator to deliver a prototype burner system, GTI and Vulcan-Hart decided that GTI would generate a concept. GTI developed the Flat Radiant Panel Burner concept that is shown in Figure 13. The key points of the burner system are:

- Combustion will occur just above the primary radiant surface
- Air for combustion will be preheated by the combustion products (recuperation)
- A secondary radiant panel aids smoothes out non-uniform radiant energy

Sketches and drawings of this concept were given to Vulcan-Hart. Vulcan-Hart made the decision that a new burner concept was much more attractive to them than the catalyst concept. Therefore GTI dropped further pursuit of the catalyst option and concentrated efforts into the burner design.

5.3.3. Outcomes

Due to the current economic climate, Vulcan-Hart was unable to actively continue participation in the design effort. GTI approached L. Vasan, president of Royal Range of California, about manufacturing a prototype of the Flat Radiant Panel Burner. Royal Range agreed to work with GTI and review the design and make recommendations. Accordingly, GTI sent the burner sketches to Royal Range for review and comment.

Royal Range and GTI discussed the sketches and design of the over-fired charbroiler. Refinements were made and GTI updated the drawings to reflect these changes. The GTI burner assembly would replace the current design burner assembly and essentially be the only new part required. A combustion air blower is currently used in the infrared design and therefore would not be an additional cost.

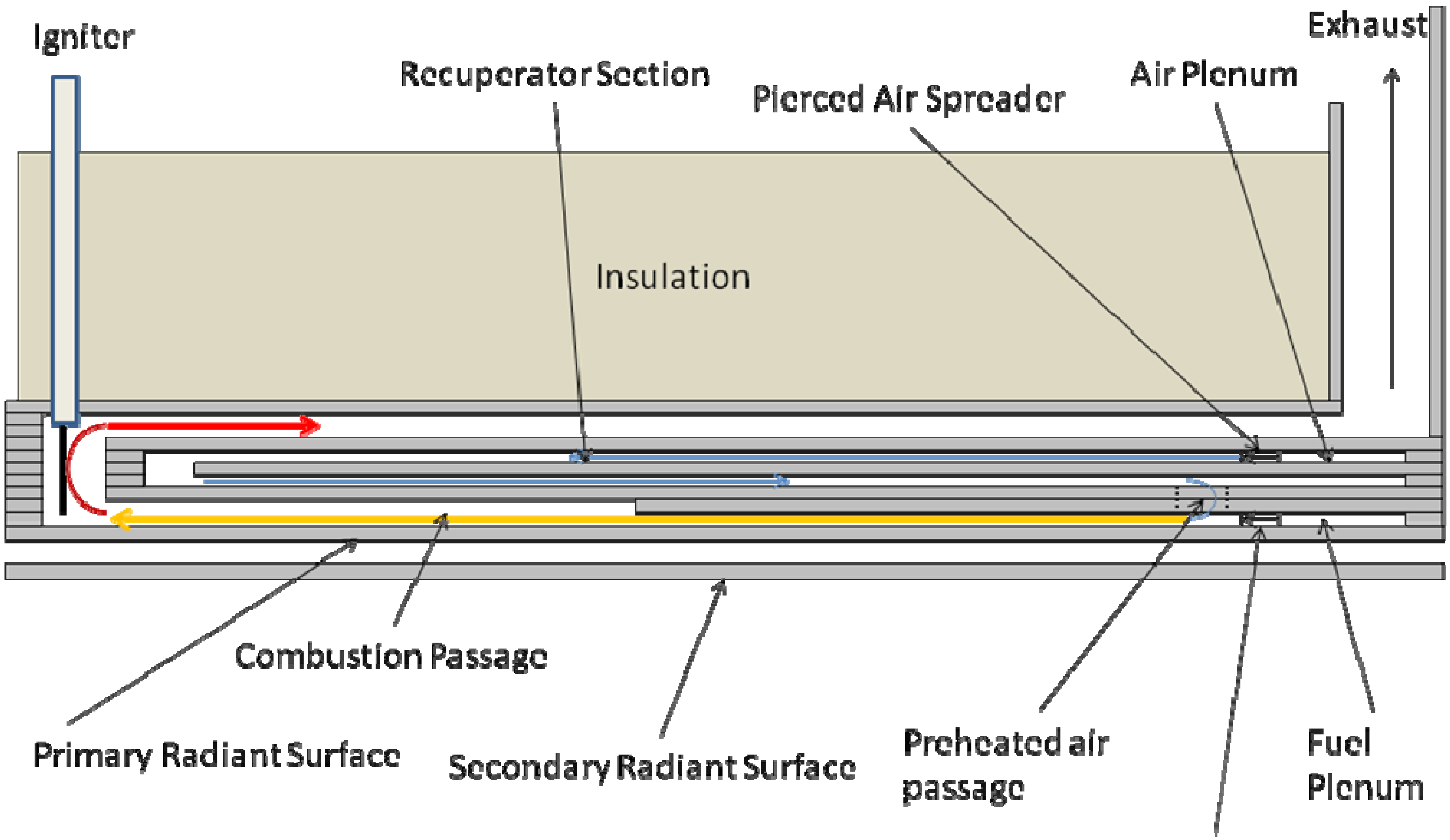

Figure 13. GTI Flat Radiant Panel Burner Concept

Source: Gas Technology Institute

5.4. Subtask 5.3: Technology Review

5.4.1. Introduction

The objective of this subtask was to conduct a technology review to select the best components for the over-fired broiler design. Criteria for selection include efficiency, performance, and uniformity.

5.4.2. Approach

GTI and Royal Range settled on the Flat Radiant Panel Burner design as a technology that could greatly increase the efficiency of over-fired broilers. The design offered the following advantages:

- Through the use of recuperation, increased cooking efficiency of better than 20%.
- Expected reduced idle consumption as burner can be modulated to lower power during idle.
- Expected improved uniformity through the use of secondary radiant surface.

5.4.3. Outcomes

GTI and Royal Range refined the drawings for the design. Figure 14 shows the final drawing package that was generated of the assembly (Cole and Johnson 2009c).

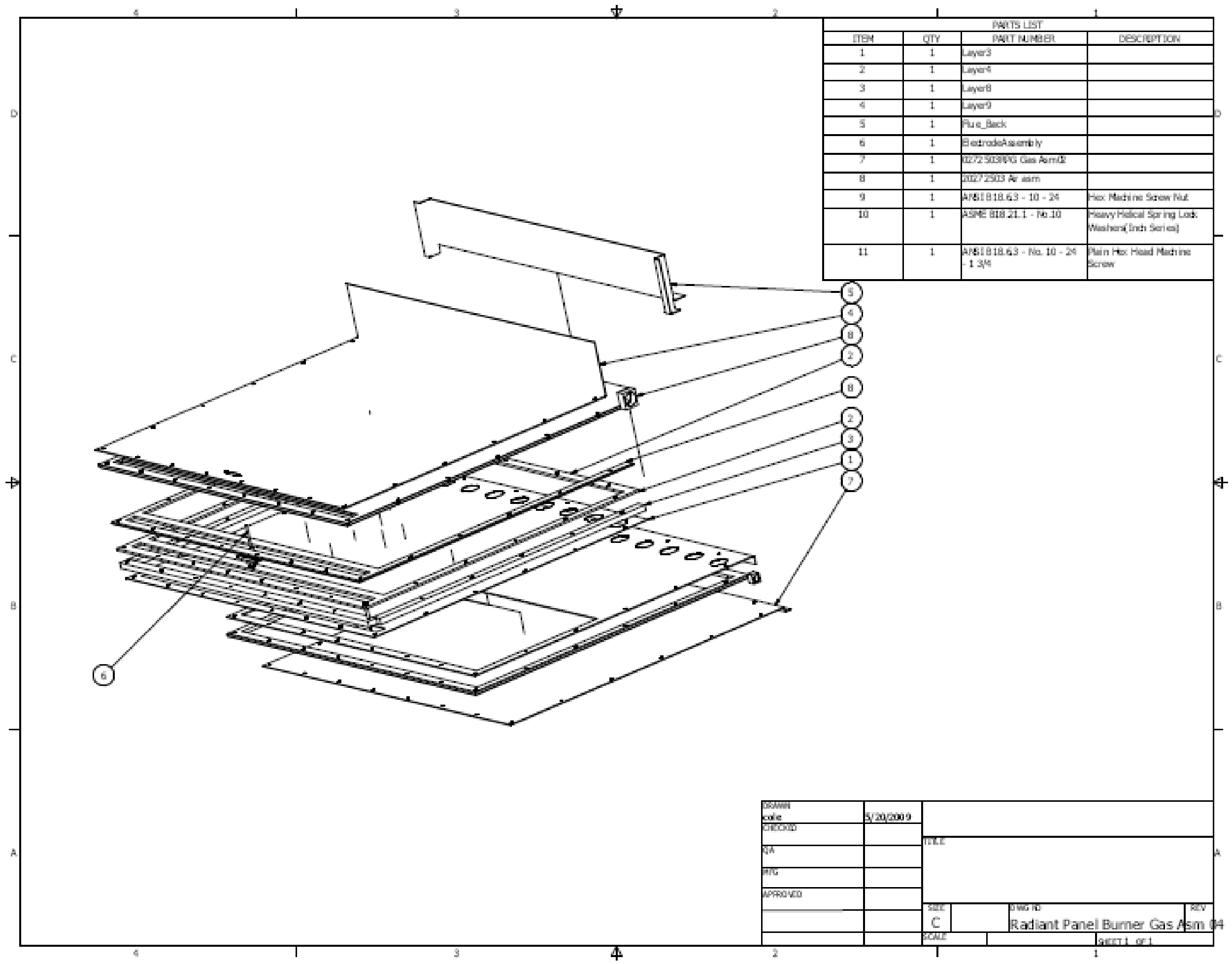

Figure 14. Final Drawing package for he Flat Radiant Panel Burner

Source: Gas Technology Institute

5.5. Subtask 5.4 Recommendations for Development

GTI had discussions with the Montague Company of Hayward, California about the burner design that is discussed here. Montague has expressed a desire to work with GTI and the California Energy Commission to carry this design into a full prototype and subsequently into production. There are still issues that need to be resolved concerning the operation of the burner. These can only be resolved by construction of a prototype and testing of that prototype.

GTI recommends that a follow on project be initiated where a bench top prototype is constructed to work on:

- Cold start ignition, firing rates and tolerance.
- Warm restart ignition, firing rates and tolerance.
- Uniformity of radiant heat from panel.
- Characterization of efficiency and heat flux at various firing rates.

After the above issues are addressed in the bench top prototype, a full working unit should be built. The full unit should be subjected to ASTM testing and product cooked on the full unit will be graded for quality conformance versus standard over-fired broilers.

Both Royal Range and Montague have expressed their desire to proceed in that direction.

This development research benefits public interest in two ways: 1) the energy savings benefits accrue directly to California citizens in the form or improved system efficiency, and 2) the environmental benefits of the reduced emissions. Currently about 170,000 gas over-fired broilers are in use in the foodservice industry, with approximately 20 percent of these are in California. The redesign broiler could result in a 25 percent reduction of the 1100 therms/yr that typical broiler uses. If 10 percent of the existing units are replaced with the new broiler, 935,000 therms/yr would be saved in California alone.

6.0 Task 6: Hybrid Optimized Tankless Water Heater

6.1. Introduction

Background

Water heater manufactures are seeking to fill the efficiency gap in residential gas-fired water heating product lines that exists between National Appliance Energy Conservation Act (NAECA) minimum and ENERGY STAR label levels, nominally ranging from 0.59 to 0.62 Energy Factor (EF) with storage tank models, and tankless models, of 0.8 EF and above, as shown in Figure 15 . Gas Appliance Manufacturers Association (GAMA) has cited the need to provide a continuum of product offerings over the EF range 0.77 to 0.86 at commensurate first cost/installed cost increments in order to stimulate efficiency upgrades beyond federally mandated minimum levels.

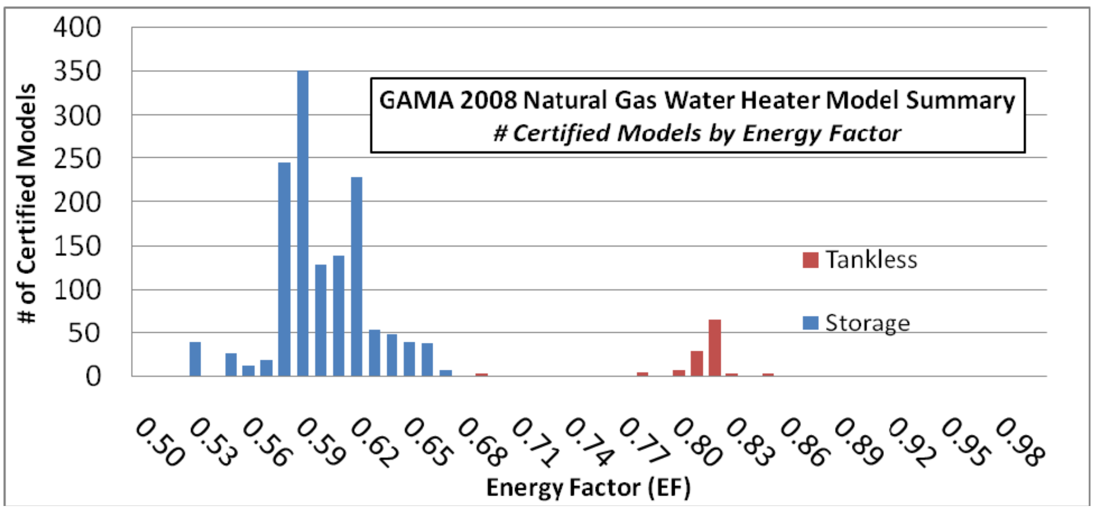

Figure 15. GAMA 2008 Distribution of Residential Gas-Fired Water Heater Models by EF

Source: Gas Technology Institute

In the Energy Commission sponsored Super Efficient Gas Water Heater Appliance Initiative (SEGWHAI), it was reported that "the replacement rate of close to a million units per year in California alone creates the potential to rapidly improve gas storage water heating efficiency … [and] reduce annual gas consumption by 17– 29 percent." However, tankless water heaters in the 0.80 EF range and above, that can achieve the higher end of this range of savings, have been significantly limited in their market penetration by high overall installed costs due to gas piping and venting upgrades in retrofit applications. A hybrid product, with its use of existing, in-place conventional gas piping and venting, can provide a more cost effective EF upgrade in those replacement markets cited by SEGWHAI and help California achieve a greater aggregate gas consumption reduction over time in the residential water heating marketplace.

In close partnership with a major manufacturer, the project team for this task performed analysis and laboratory testing to develop a Hybrid Optimized Tankless (HOT) water heater that lies within this gap, combining a lower firing rate tankless-style thermal engine with a closely coupled, downsized storage only tank to achieve a projected 0.62 to 0.73 EF performance level.

Objectives

The primary objective of this task was to develop prototype specifications for a high efficiency hybrid water heater based on a combination of existing tankless and conventional storage only technologies coupled with innovative design and control strategies (Glanville, Kalensky, and Kosar 2009). The motivation was to design a low-cost, mid-efficiency gas-fired water heater which addresses the intermittent performance and water wastage issues with whole-home tankless water heaters. Additional objectives were to provide stable water temperature on demand for dynamic loads and flow rates, peak and total water draws, and variable inlet water temperatures. The approach for the project was to design, fabricate, and lab test prototype system designs, including tankless water heater, storage or other "buffer" device, and controls, using a flexible breadboard apparatus in the laboratory, using *breadboard* as an analogy to introductory circuit design.

Under Subtask 6.1 Prototype System Design, the purpose was to utilize the Requirements Engineering and Expert Panel review processes to define the key performance attributes of a viable hybrid system, then establish prospective hybrid system configurations of integrated tankless water heater and storage only tank components, and finally design a laboratory apparatus and delineate a testing plan for evaluation of those hybrid systems utilizing industry accepted performance metrics for design optimization. Following the recommendations of Subtask 6.1, the purpose of the latter two Subtasks 6.2 and 6.3, Prototype System Fabrication and Integrated System Laboratory Testing respectively, was to fabricate a flexible breadboard arrangement of HOT water heater components in the laboratory and complete a testing procedure on baseline systems and breadboard hybrid systems testing on primary parameters including tank sizes, interconnecting piping configurations, and tankless firing rates along with secondary parameters simulating varied active and passive control strategies, explored to manage thermal stratification and smart burner delay.

6.2. Subtask 6.1: Prototype System Design

6.2.1. Introduction

As the first activity under this new product development, GTI worked with two water heater manufacturers, seven subject matter experts, and five Energy Commission staff to establish design requirements for the HOT water heater using a Requirements Engineering process. Key to any development activity, this process identified the expected performance of the HOT water heater, both technically and in the marketplace, and how it would compare to existing water heating products. As the first step, critical success factors were defined for this project:

1. Implement Requirements Engineering processes to define the hybrid system attributes.
2. Identify tankless and storage water heating components for baseline comparisons and hybrid integrations.

3. Configure these components into hybrid system integrations in accordance with design criteria from the Engineering Requirements processes.
4. Determine performance metrics for hybrid system design optimization.
5. Establish candidate hybrid system design options to meet or exceed system performance criteria from the Engineering Requirements processes.
6. Select appropriate hybrid system designs for inclusion in the follow-on subtasks for breadboard prototype construction and performance evaluation in the laboratory.

From these factors, seven specific high level design requirements and acceptance criteria were defined as shown below.

1. Projected competitive initial cost with currently available water heaters.
2. Easy retrofit installation from conventional storage water heater
3. Encourage water conservation by supporting low flow draws
    - Sustain hot water at minimum of 0.3 gallons per minute (gpm)
    - Flow hot water within four seconds of draw
4. Minimize the cold water sandwich effect
    - Minimum of 100 °F exit temperature
    - Heating to within ±2 °F of set point
5. Support simultaneous hot water draws for normal residential uses.
    - Support a 70 °F rise at 5.0 gpm for three minutes
6. Energy efficiency comparable to tankless systems
    - At least 20% better than conventional storage only systems
    - At most 5% less efficient than tankless systems
    - EF at $0.62 < EF < 0.73$ for greater than 10 gallons per day (gpd)
7. Strong potential for meeting South Coast Air Quality Management District NO_x emissions regulations.

These Engineering Requirements were subject to later review by an Expert Panel, which shared many of the members of the previous working group but with key additions from among the tankless water heater manufacturers and California utilities. This panel provided further separation of goals by retrofit and new construction scenarios by placing emphasis on ease of installation in existing applications, including use of ½" gas lines an Category I/Type B vents already in place.

The specific Subtask 6.1 objectives were to:

1. Implement findings from the Requirements Engineering processes to define the hybrid system attributes.
2. Identify tankless and storage water heating components for baseline comparisons and hybrid integrations.

3. Configure these components into hybrid system integrations in accordance with design criteria from the Requirements Engineering processes.
4. Determine performance metrics for hybrid system design optimization.
5. Establish candidate hybrid system design options to meet or exceed system performance criteria from the Requirements Engineering processes.
6. Select appropriate hybrid system designs for inclusion in the follow-on subtasks for breadboard prototype construction and performance evaluation in the laboratory.

6.2.2. Approach

1. Convene an Expert Panel and review the findings from the Requirements Engineering process for the HOT water heater. Finalize the HOT water heater design requirements and determine the representative baseline water heating systems for which to compare HOT water heater performance.
2. With a manufacturing partner, develop a test protocol to comparatively evaluate baseline storage, baseline tankless, and HOT water heating systems. The protocol should consist of both standardized certification test procedures and also targeted "performance" tests, designed to both represent typical loads and to highlight the weaknesses of the respective baseline systems relative to an ideal HOT water heater configuration.
3. Evaluate the performance of baseline and HOT water heating systems through available and custom generated simulation tools. First validate the use of said tools on baseline systems as compared to published and certified data, and then extend the simulation to the definition of a test protocol to frame the target performance required by the HOT water heater. Also evaluate the performance of the range of HOT water heater primary parameters, which are storage volume and firing rate, and component configurations to establish the desired range of the testing in the laboratory.
4. Based upon the simulated HOT water heater performance of varying storage volumes and firing rates relative to baseline system performance, recommend a range of HOT water heater primary parameters that are at or near target performance requirements for experimental evaluation. Using simulation tools, explore the effect of varied control strategies and system integrations (e.g. tap locations) and their effect on stratification dynamics and overall efficiency.
5. Design a flexible laboratory breadboard which can accommodate both the two baselines and the target range of HOT water heater storage volumes and firing rates.

6.2.3. Outcomes

One of the primary results from this Subtask was the identification of the HOT water heater design test matrix, consisting of storage component volumes and tankless component firing rates. This matrix, as shown in Figure 16, identifies the likely optimum (light gray) and oversized (dark gray) combinations of storage and firing rates. The shape of the likely optimum cell grouping is physically intuitive, as the larger storage volumes have efficiency penalties and long recovery times, rendering high firing rates ineffective, and smaller storage volumes have fast recovery and depletion rates, best taken advantage of by a higher firing rate. For purposes of identification, these parameters are referred to as the *primary* design parameters, to distinguish later from the refined *secondary* design parameters, consisting of the dip tube length, thermostat location, and thermostat dead band.

Buffer Storage Volume / Burner Firing Rate	10 gal	15 gal	20 gal	25 gal	30 gal	40 gal
40,000 Btu/hr						
50,000 Btu/hr						
60,000 Btu/hr						
75,000 Btu/hr						
100,000 Btu/hr						
125,000 Btu/hr						
150,000 Btu/hr						
175,000 Btu/hr						
200,000 Btu/hr						

Figure 16. Primary Hot Water Heater Prototype Desgin Matrix

Source: Gas Technology Institute

Based upon the Engineering Requirements process findings, Expert Panel review, the manufacturing partner input, and GTI staff analytical evaluations, a test protocol was developed to highlight the potential strengths and weaknesses of the two baseline systems and the HOT water heater combinations in between. The protocol consists of five test categories: a Sustained Low Flow Draw, an Endurance Low & Mid and a Short Duration High Peak Draw, a Cold Water Sandwich Draw, the DOE First-Hour Rating (FHR) Test, and a 24-Hour Simulated Use Test (Federal Register 1998) using both the DOE and a more realistic draw pattern. This testing will validate the performance of the baseline equipment, i.e. the tankless and conventional storage only systems, that were initially established with product literature and modeling results. The testing will also establish the potential of the hybrid design configurations to meet or exceed the established engineering requirements. Note that the goal of this first subtask is not to identify the optimal configuration, rather it is to identify an acceptable range of parameters for laboratory testing to determine the optimum in the follow-on subtasks. The capability for testing this range of parameters for baseline and hybrid systems will be built into the breadboard testing apparatus in the laboratory.

Through single-nodal, multi-nodal, and Computational Fluid Dynamics (CFD) modeling, these storage and firing rate combinations were run through the simulated test protocol. In addition to providing the basis for Figure 16, this modeling studied the HOT water heater sensitivity of mixing dynamics to thermostat location, tap location, and draw rates, with a few resulting design insights highlighted here:

1. A HOT water heater configuration with the cold makeup water blending downstream of the tankless water heater component was found to be superior, as it allowed for smaller firing rates.
2. Well-mixed conditions are anticipated for the range of storage volumes employed when the circulation pump is activated.
3. Stratification, a key parameter to transient performance, is generated within a tank primarily as a result of incoming cold makeup water, with little contribution due to uneven lateral heat transfer from inner wall and center flue surfaces.
4. During draws prior to circulation pump activation (i.e. the call for heat), use of side taps for cold makeup water reduced stratification greatly relative to dip tubes, reducing delivered water temperatures.

While the tradeoffs of varying the storage volume or firing rate may be generally intuitive, their effects throughout the test protocol simulating the dynamics and varied loads of regular use are not.

Major Deliverables

1. Selection and development of modeling capabilities to evaluate baseline and hybrid system performance in advance of testing. This modeling proved necessary to narrow the range of hybrid design parameters to a prototype system matrix feasible for fabrication and testing.
2. Delineation of the hybrid water heater breadboard apparatus for fabrication and generation of the testing plan for evaluations of those integrated systems in the laboratory.

6.3. Subtask 6.2: Prototype System Fabrication & Subtask 6.3: Integrated System Laboratory Testing

6.3.1. Introduction

To accommodate the desired range of HOT water heater tank storage volumes and tankless heater firing rates, the manufacturing partner donated modified versions of a tankless water heater and several point-of-use and electric storage tanks. The storage tanks were modified to have multiple ports, accommodating the tap points for draws, the circulation loop running to the tankless component, and instrumentation. The tankless water heater was modified to operate in two modes, in modulating mode, or "normal" out-of-the-box operation, and fixed-firing mode, where the firing rate is fixed at a discrete setting. In this pumped circulation loop, the heater is flow activated, so to operate the tankless water heater when the thermostat calls for heat the circulation pump is powered. The baseline and HOT water heater system components as tested in the breadboard are summarized in Table 3.

The experimental breadboard laboratory setup shown in Figure 17 was designed and constructed to have the flexibility required by the variable baseline and HOT water heating systems while minimizing the relative biases from one system tested to another and absolute biases to certified published test data. Note that while the breadboard will be used for the DOE First Hour Rating and 24 Hour Simulated Use test and the instrumentation and test conditions are per the test procedures, GTI is performing tests within its Residential/Commercial laboratories, which are not certified per GAMA requirements. Therefore, while some results are from DOE test procedures, they are only relevant in relative comparison to experimental data from this project and are not directly comparable to First Hour Ratings (FHR) or EF published by manufacturers.

Table 3. Breadboard Water Heating Component Summary

Water Heating System	Storage (gallons)	Firing Rate(s) (Btu/hr)
Baseline Conventional Storage Only	40	36,000
Baseline Tankless	n/a	19,000 – 199,900
HOT Water Heater	10, 15, 20, 30	50,000, 75,000, and 100,000

Source: Gas Technology Institute

Figure 17. Photo of Hot Water heater Setup

Photo Credit: Gas Technology Institute

The specific Subtask 6.2 and 6.3 objectives were to:

1. Fabricate a flexible breadboard apparatus to accommodate different arrangements of HOT water heater components in accordance with Subtask 6.1 design configurations.
2. Incorporate interconnecting piping options between the tankless and storage only tank components, along with variable control options as well, for laboratory testing.
3. Detail and finalize a laboratory test plan based on Subtask 6.1 deliverable.
4. Perform baseline laboratory testing on conventional stand alone storage and tankless water heaters using the flexible breadboard apparatus.
5. Perform laboratory testing on hybrid system design configurations using a procedure that varies primary and secondary system design parameters to yield optimal characteristics of a hybrid water heater.

6.3.2. Approach

1. Select, procure, fabricate, and instrument the necessary components to construct the flexible breadboard testing apparatus required for the range of testing outlined in Subtask 6.1. Where possible, use existing tankless and buffer storage only tank component technologies. Develop control algorithms to automate long term tests and to control the HOT water heater components with varied control strategies.
2. Experimentally evaluate HOT water heater component behavior, including: stratification dynamics during varied loads and piping configurations, efficiency of steady state firing at different rates, and parasitic electric loads. Also validate CFD modeling performed under the previous subtask.
3. Execute test protocol on baseline storage & tankless water heaters and all HOT water heater combinations and configurations.
4. Through data analysis, determine optimum combinations of HOT water heater storage and firing rates. Identify areas for optimization of secondary parameters (e.g. control strategy) for improved efficiency and performance.
5. Perform focused testing on select HOT water heater combinations of storage and firing rate to additional quantify improvements through secondary parameter optimization.
6. Outline recommended specifications for HOT water heater prototypes with the anticipated efficiency and other performance attributes.

6.3.3. Outcomes

Employing the primary parameter matrix of HOT water heating system components resulting from Subtask 6.1, consisting of storage tank volumes and burner firing rates, a laboratory breadboard apparatus capable of accommodating a range of these parameters was constructed and instrumented. Following shakedown of the hardware and data acquisition system the baseline systems, consisting of a 40 gallon 36,000 Btu/hr gas-fired storage water heater and a 200,000 Btu/hr modulating tankless water heater, were tested and served as the ends of the performance spectra. Executing the test protocol as developed under Subtask 6.1, the baseline systems performed as expected, relative to typical system performance and certified product test results. Baselining also served to validate the laboratory breadboard test apparatus, for accuracy and controllability.

Prior to executing the test protocol on the HOT water heater systems, individual components were tested, resulting in: (1) identification of experimental biases from use of the modified tankless water heater in the discrete single-stage firing mode, (2) quantification of tankless electric parasitic loads resulting from said biases and normal operation, (3) selection of dip tubes of varying lengths as the superior interior piping configuration and an optimum exterior piping configuration, and (4) analysis of the effect of well-mixed conditions, induced by the circulation pump, on the quality of hot water draws.

Through breadboard laboratory testing, the HOT water heater systems of varying tank volume and firing rate showed consistent improvement over tankless water heaters in low flow and intermittent draw patterns and improvement over conventional storage based water heaters in estimated First Hour Ratings (FHR) and EF. However, by virtue of the reduced onboard storage and firing rates compared to the two baseline systems, the HOT water heater systems showed reduced performance in peak draws of 4.5 gpm and above. As all breadboard HOT water heater combinations exceeded baseline FHRs but not EFs, the latter was selected for use with further optimization. From the primary parametric testing of the storage and firing rate variation, an optimum 75,000 Btu/hr single firing rate tankless water heater coupled with 20 gallons of buffer storage was determined and achieved a 0.63 EF without, and 0.68 EF with, suppression of the 18 hour standby period recovery in the standard DOE EF test, a practiced technique amongst water heater manufacturers.

Highlighting the 24 Hour Simulated Use Test with the DOE Draw Profile, there exists much ground to be covered in minimizing the inefficiencies outlined in Figure 18. For the combustion efficiency, driving down the stack losses during firing, for continued retrofit applicability and for competitive pricing it is assumed that a condensing tankless component is not a possibility for the base HOT water heating system. That leaves the following areas for optimization (1) reduced standby cycling through smart controls, reduction in exposed fittings, and improved insulation/materials, (2) reduced electric parasitic loads through combustion systems and circulation pumps appropriate to an integrated prototype, and (3) increased energy delivered through smart burner delay and stratification management. As the third optimization area is the most complex, it warranted secondary parametric testing.

Through secondary parametric testing, the estimated energy efficiency increase associated with burner firing delay was quantified through optimization of the delivered efficiency for a focused range of storage volumes and firing rates, centering on this initial optimum of 75,000 Btu/hr and 20 gallons. Additional efficiency penalties associated with the use of a modified, modulating tankless water heater were quantified relative to an actual single stage tankless water heater operation, including the modulating unit’s continuous combustion fan operation and oversized heat exchanger. Through summation of these projected prototype energy efficiency gains, the HOT water prototype has a projected EF of 0.71 – 0.73. Coupled with its use of existing ½" gas lines and Category I/Type B venting, this hybrid water heater design potentially provides a more economically viable EF upgrade than tankless water heaters in retrofit applications.

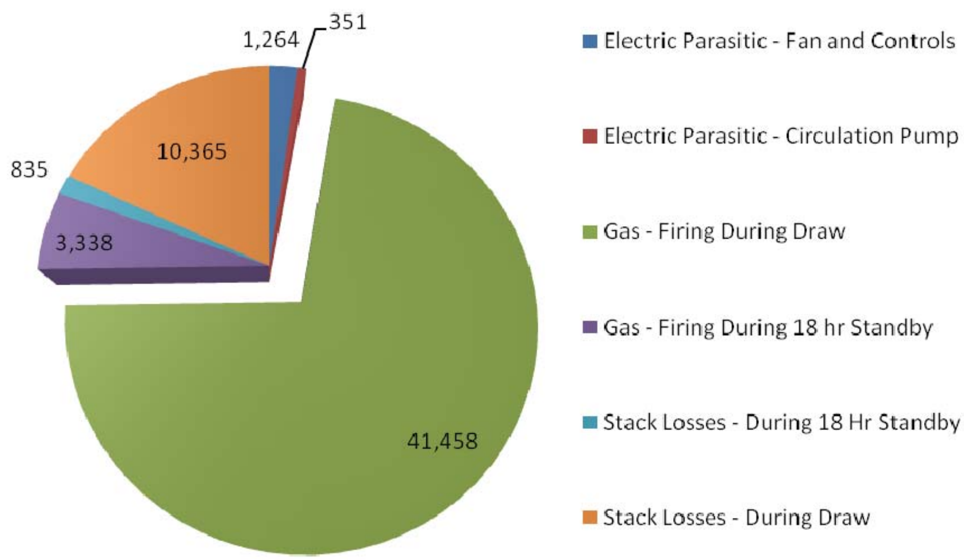

Figure 18. DOE Draw Profile 24 Hour Simulated Use test Energy Inputs for 20 Gallon 75,000 Btu/hr (values reported in Btus)

Source: Gas Technology Institute

GTI is currently pursuing prototyping activities with the manufacturing partner through a gas industry funded follow-on project, which will fabricate and test a HOT water heater prototype(s). In addition to validating efficiency and other performance projections of this subtask, keeping unit and installed costs low, through retrofit ability with ½" gas lines and Category I/Type B venting, is a strong priority.

Major Deliverables

1. Fabrication and instrumentation of Hybrid Optimized Tankless (HOT) water heater breadboard testing apparatus composed of modified off-the-shelf components.
2. Generation and execution of test plan for baseline and HOT water heater systems. Additional testing included: evaluation of opportunities for optimization through advanced control strategies and stratification management, identification of breadboard experimental biases, and experimental validation of prior modeling.
3. Final report documenting Task 6 activities, including computer modeling, breadboard fabrication, test procedures, performance results, and product prototype recommendations.

6.4. Hybrid Optimized Tankless Water Heater Conclusions and Recommendations

The conclusions of this task are that the HOT water heater breadboard apparatus performed as expected during baselining and when tested at the edges of the performance spectra. From the primary parametric testing of the storage and firing rate variation, an optimum 75,000 Btu/hr single firing rate tankless water heater coupled with 20 gallons of buffer storage was determined. This design achieved a 0.63 EF without suppression of the 18 hour standby period recovery in the standard DOE EF test, and 0.68 EF with suppression of the standby period recovery - a practiced technique amongst water heater manufacturers. Areas for optimization were identified during the 24 hour DOE test and through secondary parametric testing. Summing all efficiency gains projected during this testing, the HOT water prototype could reach an EF of 0.71 – 0.73. Coupled with its use of existing ½ inch gas lines and Category I/Type B venting, this hybrid water heater design potentially provides a more economically viable EF upgrade than tankless water heaters in retrofit applications.

Based on these findings, a hybrid product prototype development is pending with a major domestic water heater manufacturer. During the course of this potential follow-on activity, it is recommended that the projected 0.71 to 0.73 EF performance level be validated with a prototype in the laboratory. Additionally, the compatibility with Category I/Type B venting must be confirmed along with the ability to meet South Coast Air Quality Management District (SCAQMD) emission limits of 10 ng NO_x /J output (or 14 ng NO_x /J output if over 75,000 Btu/hr firing rate). Finally, first cost must be quantified for such a product offering and installed costs determined to establish the cost effectiveness of this level of EF upgrade, especially in retrofit applications.

In terms of benefits to California, water heater manufactures have cited the need to provide a continuum of product offerings over the EF range at commensurate first cost/installed cost increments in order to stimulate efficiency upgrades beyond federal mandated minimum levels. In the Energy Commission sponsored Super Efficient Gas Water Heater Appliance Initiative (SEGWHAI), it was reported that "the replacement rate of close to a million units per year in California alone creates the potential to rapidly improve gas storage water heating efficiency … [and] reduce annual gas consumption by 17– 29 percent". However, tankless water heaters in the 0.80 EF range and above, that can achieve the higher end of this range of savings, have been significantly limited in their market penetration by high overall installed costs due to their high initial first cost plus ½ inch to ¾ inch gas piping and manufacturer specific Category III venting upgrades in retrofit applications. A hybrid product, with its use of existing ½ inch gas piping and Category I/Type B venting, can provide a more cost effective EF upgrade in those replacement markets cited by SEGWHAI and help California achieve a greater aggregate gas consumption reduction over time in the residential water heating marketplace.

7.0 References

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8.0 Glossary

ANSI	American National Standards Institute
ASTM	American Society of Testing and Materials
CFD	computational fluid dynamics
CPR	critical project review
DOE	Department of Energy
EF	Energy Factor
FHR	First Hour Rating
FNi	Fisher-Nickel Inc.
FSTC	Food Service Technology Center
GAMA	Gas Appliance Manufacturers Association
GTI	Gas Technology Institute
HVAC	heating, ventilating, and air conditioning
NAECA	National Appliance Energy Conservation Act
NAFEM	North American Association of Food Equipment Manufacturers
PIER	Public Interest Energy Research
SCAQMD	South Coast Air Quality Management District
SEGWHAI	Super Efficient Gas Water Heater Appliance Initiative
SMP	Sustaining Membership Program
VOC	Volatile Organic Compound